

The Development of Computer Graphics For Large Scale Finite Element Codes

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The development of an extensive series of computer generated graphics packages for large-scale finite element analyses is described. Suitable examples illustrating the means by which such graphics are used for eliminating input errors, output data reduction, report preparation, and radically reducing overall task time spans are presented. Programs for which such computer generated graphics have been developed include two-dimensional geometries, general structures and arbitrary three dimensional solids while special purpose versions have been used for such applications as movie generation and interference studies. Finally, Lockheed's recent activities in the development of interactive computer graphics for large scale production finite element analysis are discussed and illustrated.

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SECTION I INTRODUCTION

THE NEED FOR GRAPHICS

The rapid development of the finite element method together with its widespread acceptance and increasing application in structural mechanics has brought with it a series of problems in addition to its many obvious advantages. Such problems as programming errors, machine accuracy and element shortcomings have been fairly commonplace. Nonetheless, the major problems have undoubtedly been concentrated in three areas: the difficulty in ensuring the input of correct mathematical models, the questionable ability to assess the validity of results, and, thirdly, the problems associated with assimilating, compressing, and organizing the voluminous output of data inherent in a finite element analysis into a usable engineering format and presentation. In all these areas it is clearly evident that the development of an extensive graphics capability simultaneously with the implementation of a finite element code would minimize and, in most cases, eliminate such problems. Over the past five years, therefore, the Missile Systems Division of Lockheed has pursued, as a major research effort, the development of a wide range of graphics packages for our library of large scale finite element programs, and these packages are now production features for all current codes.

The need for graphics was quickly established with the advent of the original Wilson axisymmetric code in 1965 (Reference 1). Reduction of the printed output from the first major analysis task required two months to complete, a timespan clearly unacceptable for a production oriented analysis group. Additional unfortunate early discoveries regarding the sensitivity of finite element analyses to such parameters as element aspect ratio and correct nodal geometry only served to emphasize the importance of graphics for input checks and determining validity of results. Finally, experience has shown that extensive graphics packages rapidly change from desirable aids to mandatory requirements as the complexity of programs and analyses increases, and as higher-order elements are developed and utilized (References 2, 3 and 4). Elements such as nonlinear isoparametric hexahedral solids (and the structural models for which they are employed) possess a degree of complexity far removed from earlier, two-dimensional constant strain formulations. The output data generated by such elements ranges from the ample to the awe-inspiring, thereby demanding that extensive graphics packages be present in order that the analyst can perform his studies with any semblance of confidence and rationality of scheduling. Hence, the true value of these graphics packages lies in their ability to

reduce errors, task time-spans, and computer and reporting costs. With these aims in mind, graphics in the batch process mode can be applied in two areas: prior to solution as a means for model debugging, and following execution as a method of display and data reduction. The debugging of a model using graphical model play-back allows the user to quickly identify and correct model errors, thereby eliminating the possibility of a faulty model being assumed correct and run for results which are obviously erroneous, or worse yet, containing hidden errors which could go undetected even through the output data reduction stage. One node out of place or the addition of an unwanted element could easily remain hidden through task completion, while destroying the entire model's validity. However, errors in input nodes and elements stand out clearly on a plot of the structure (Figure 1), particularly when the ability to automatically rotate and view the model from any position is present.

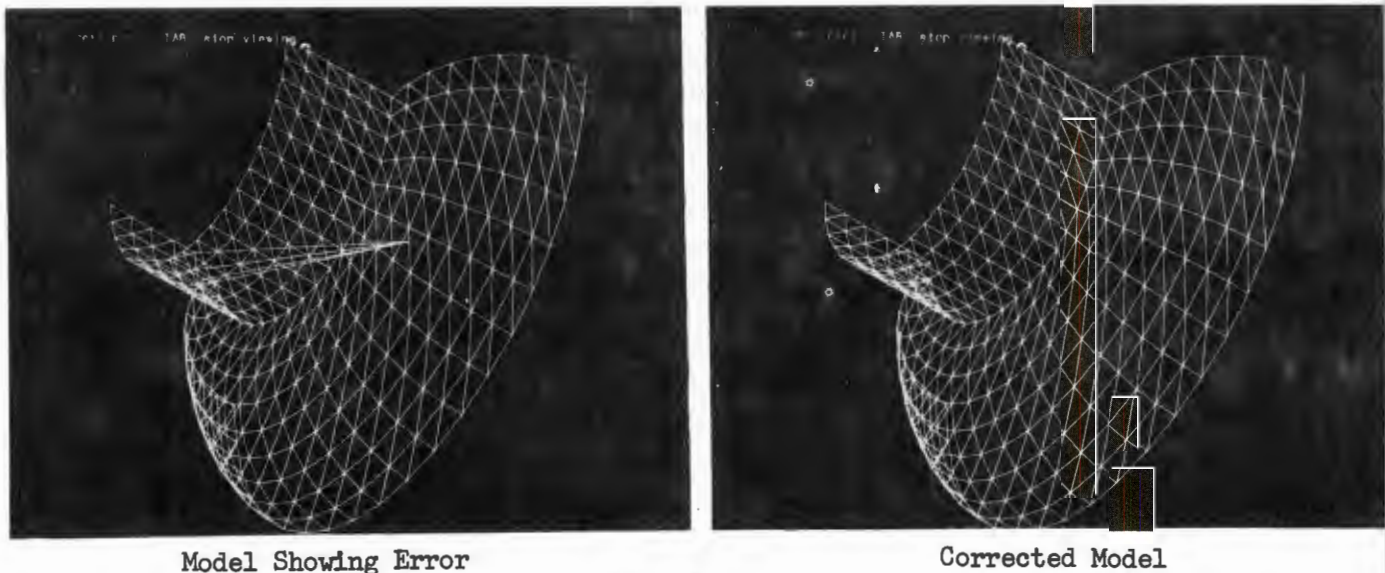


FIGURE 1
DISPLAY OF INPUT ERROR

Thus, for input, time is saved by the user's ability to quickly and thoroughly debug his model, while costs are minimized by eliminating the need for re-runs to obtain correct results. At the other end of the scale, computer graphics are needed as a means for reduction of output data both in an initial scanning mode and in producing a final format ready for direct insertion into a report. To accomplish these output tasks the engineer requires such graphical tools as element and nodal numbering displays, deflected figures, automatic stress and strain cuts, and isostress and isostrain contouring. For example, a deflected picture of the structure, by itself or superimposed over the undeflected figure, condenses all printed deflection output into a single visual entity. Another advantage of a deflected plot of the structure is that by magnifying the deflections and then plotting the structure, areas in which small deflections occur are exaggerated to a degree which allows the viewer to quickly determine the overall validity of the pattern of the model's deflections.

Plots of output results along any cut through the structure, together with a picture of the model defining the cut being taken, give the user a compact set of graphs showing stress and strain variation throughout any region in the model which can be compared to strain gage data (when available) along an identical cut, or inserted directly into a report. This concept compacts large quantities of output data into a few pertinent cuts allowing the user to pick out element stresses and strains at a glance. As presently developed, anywhere from one to nine of these graphs can be generated on a single page, depending on the quantity of data per graph and the amount of information to be displayed overall. Such schemes allow the engineer to significantly compress the area needed to present his analytical results.

An even larger amount of output data can be compressed into one picture through the use of contour plots. Using such plots the engineer is able to view the stress or strain pattern of an entire surface. Such patterns point out areas having high stress gradients. The first contouring program obtained by LMSC (Reference 5) contoured only data from a rectangular grid, but the same method of contour generation has now been adapted to handle models having arbitrary boundaries and deleted interior regions.

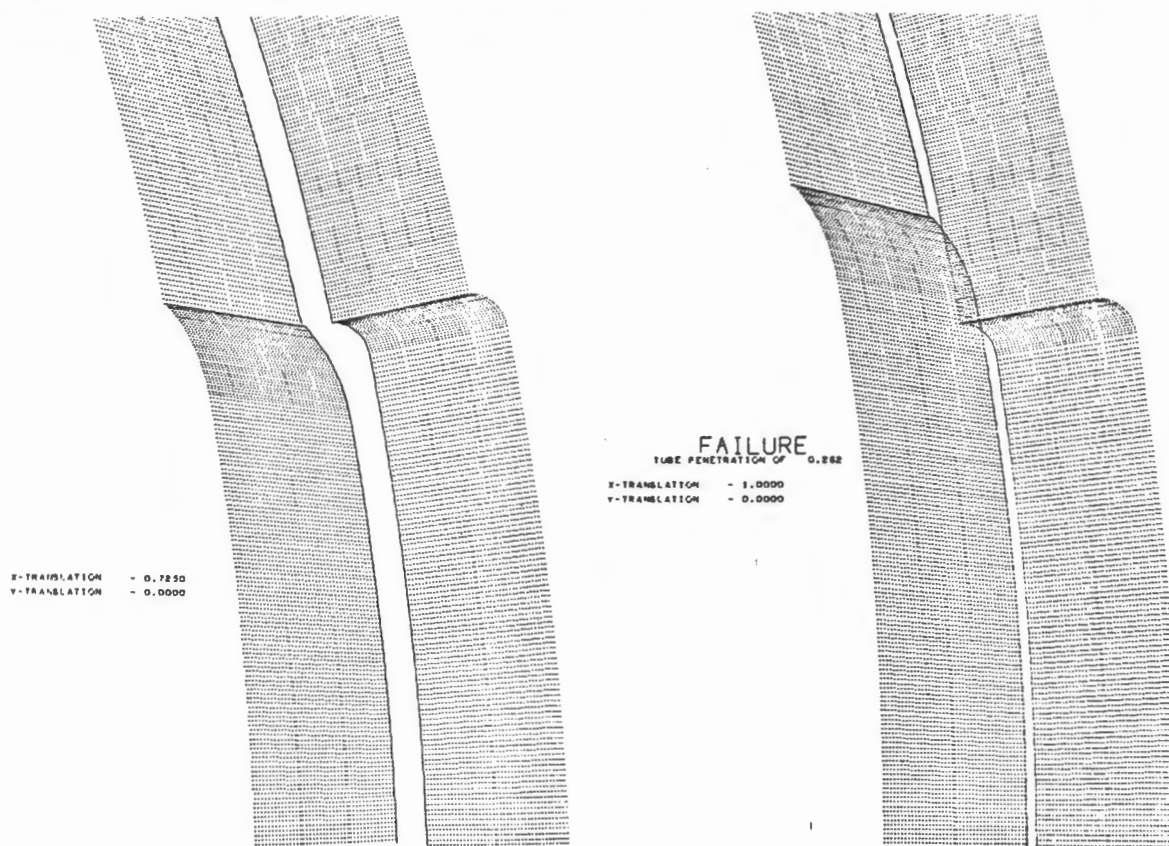


FIGURE 2
 GRAPHICAL DISPLAY OF MISSILE STRUCTURE AND
 LAUNCH-TUBE INTERFERENCE STUDY FOR A SERIES
 OF POTENTIAL MISSILE ROTATIONS AND TRANSLATIONS

As noted in Reference 6, a large percentage of time on each structural analysis task is dedicated to the generation of a final report. With the use of computer generated plots this portion of a task is reduced to a minimum. The results are compact, complete, and entirely machine generated in a format which can be inserted directly into a final report, including page number, dates, names, and contract numbers. This report format is totally flexible and, hence, may be output directly as an 8-1/2 x 11 page with sufficient margins on all sides, or joined with additional data and output on an 11 x 17 page as demonstrated in Reference 7.

Neither is the use of computer generated graphics limited solely to the presentation of structural models and analytical results, for such schemes can be used to produce a display of a structure's proposed operating function or a visual representation of theoretical data such as the determination of interference failure limits for a missile and launch-tube interface for a large matrix of possible rotations and translations of the missile within the tube (Figure 2). Furthermore, it is often advantageous to present graphics data in the form of a movie to enhance visual representation. For example, a missile wing (Figure 3) was still in the preliminary design stage when a movie was completed by means of computer graphics which showed the proposed wing pivoting to its deployed position and deflecting under the maximum flight load conditions. Such movies have also been used to show the reaction of a model to a given load or to display various bending and torsional modal shapes. A model may also be positioned in space and then spun around and viewed from all sides, or an element-by-element build-up of the structure can be displayed to enable close examination of complex interactions between different sections of the model.

In the following section of this paper a detailed description of the means by which LMSC has employed such graphics packages to substantially reduce the time span and cost for both the input and output of finite element analyses is described in detail, together with recent extension of such activities into the area of interactive computer graphics.

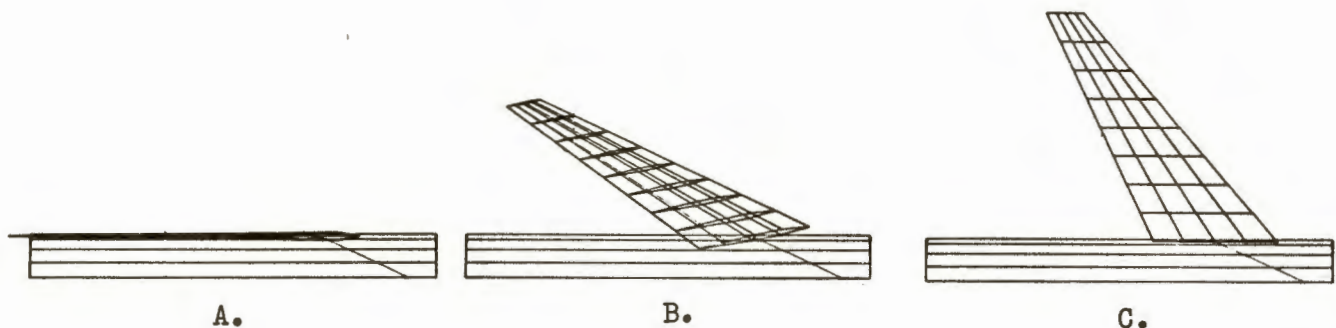


FIGURE 3

WING STRUCTURE SHOWING VARIOUS STAGES OF DEPLOYMENT

SECTION II

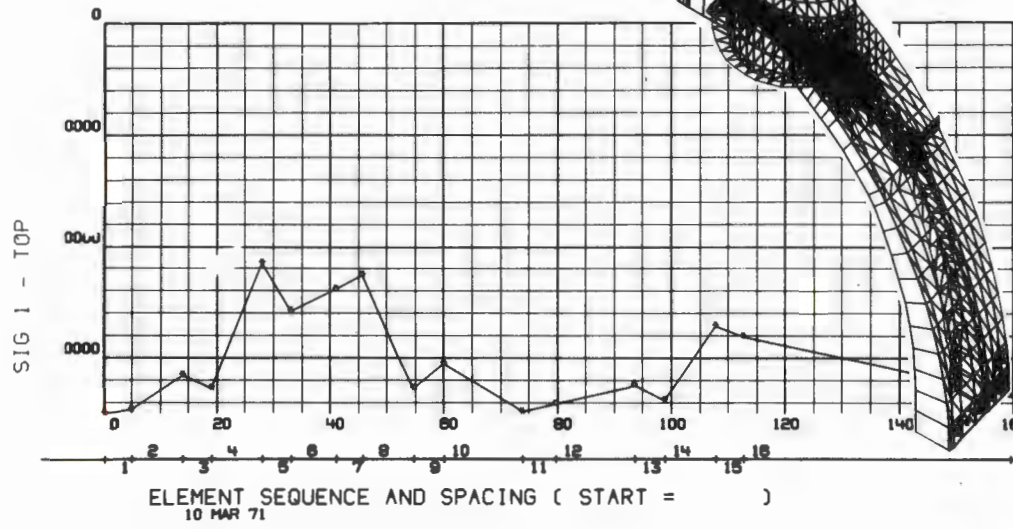
GRAPHICAL PRODUCTION TOOLS

GENERATION OF GRAPHICS PACKAGES

There are a variety of machines currently available which can be used to present computer generated graphical data including both pen and CRT plotters. Lockheed's needs for a plotter with both hard copy and microfilm output, rapid plot generation, and a high degree of resolution have over the past eight years been filled through the use of a CRT plotter, specifically the Stromberg-Carlson 4020 system (generating plots in about .25 seconds and having 1024 x 1024 addressable rasters). Additional flexibility and resolution have recently been realized through the implementation of an III FR80 CRT plotter having 16,300 x 12,900 addressable rasters together with variable line width and character size. The improved resolution offered by the FR80 is illustrated by Figure 4. Every machine has different individual features (Reference 8) such as method of generation, resolution and speed, but the basic routines available to the programmer are the same. The generation of any graphical output, no matter how complex, is merely the manipulation of these few basic routines: line drawing, character display, scaling, and grid generation. The programmer uses these routines to pass his model's node and element information together with his output results from the computer to the display unit in a mode suited to his display needs. The display unit may be a hard copy or microfilm generation or any of the number of interactive display scopes, but in general the large scale batch process user relies on the hard copy option.

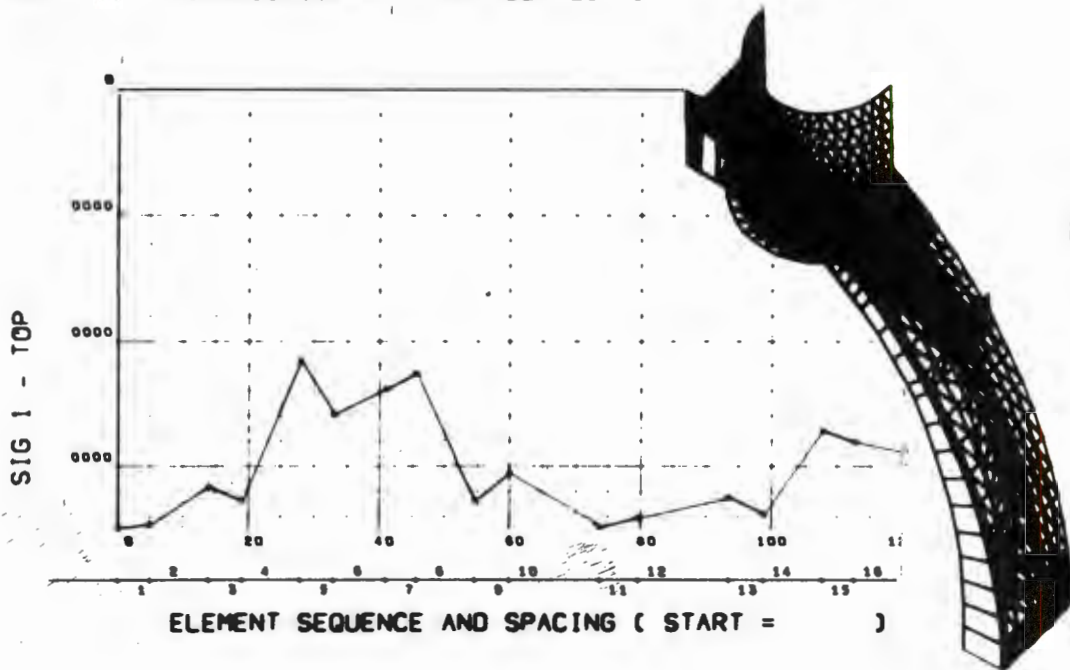
The structural graphics packages developed thus far fall into three main categories, depending on the finite element codes to which they are linked: 1.) Two-dimensional structures, 2.) Mixed structures, and 3.) Arbitrary solids. Each type of code varies in the form of model generated and the output quantities determined, while a similar variation exists in their accompanying graphics packages. The following section describes the current graphics schemes employed to reduce and display data for each of these three types of structural codes. A final section discusses the implementation of an interactive graphics mode for such codes, which further reduces task time span and costs.

ANY SINGLE STRESS QUANTITY MAY BE PLOTTED



FR-80

ANY SINGLE STRESS QUANTITY MAY BE PLOTTED



SC-4020

ANY SINGLE STRESS QUANTITY MAY BE PLOTTED

FIGURE 4
COMPARISON OF OUTPUT FROM TWO C.O.M. PLOTTERS

TWO DIMENSIONAL GRAPHICS

These codes analyze structures in which the finite element model can be defined in two dimensions. Examples are axisymmetric structures and plane stress structures of constant thickness. In the finite element approach the continuous structure is replaced by a system of axisymmetric elements which are interconnected at circumferential joints or nodal circles. Hence, such structures only require that graphics packages work with and display on the basis of a single XY coordinate system.

The model for an axisymmetric program makes use of mesh generation routines in which the user inputs model boundaries and a mesh pattern, with the program using this data to generate the finite element model (Figure 5).

While setting up the initial model, a user can vary the grid intensity in the critical regions to get more detailed results which may later be presented as contour plots (Figure 6), at the same time setting up definite element boundaries between different materials. A model can then be graphically displayed both in its entirety, or with any portion of the structure blown up to clarify a region with a denser grid.

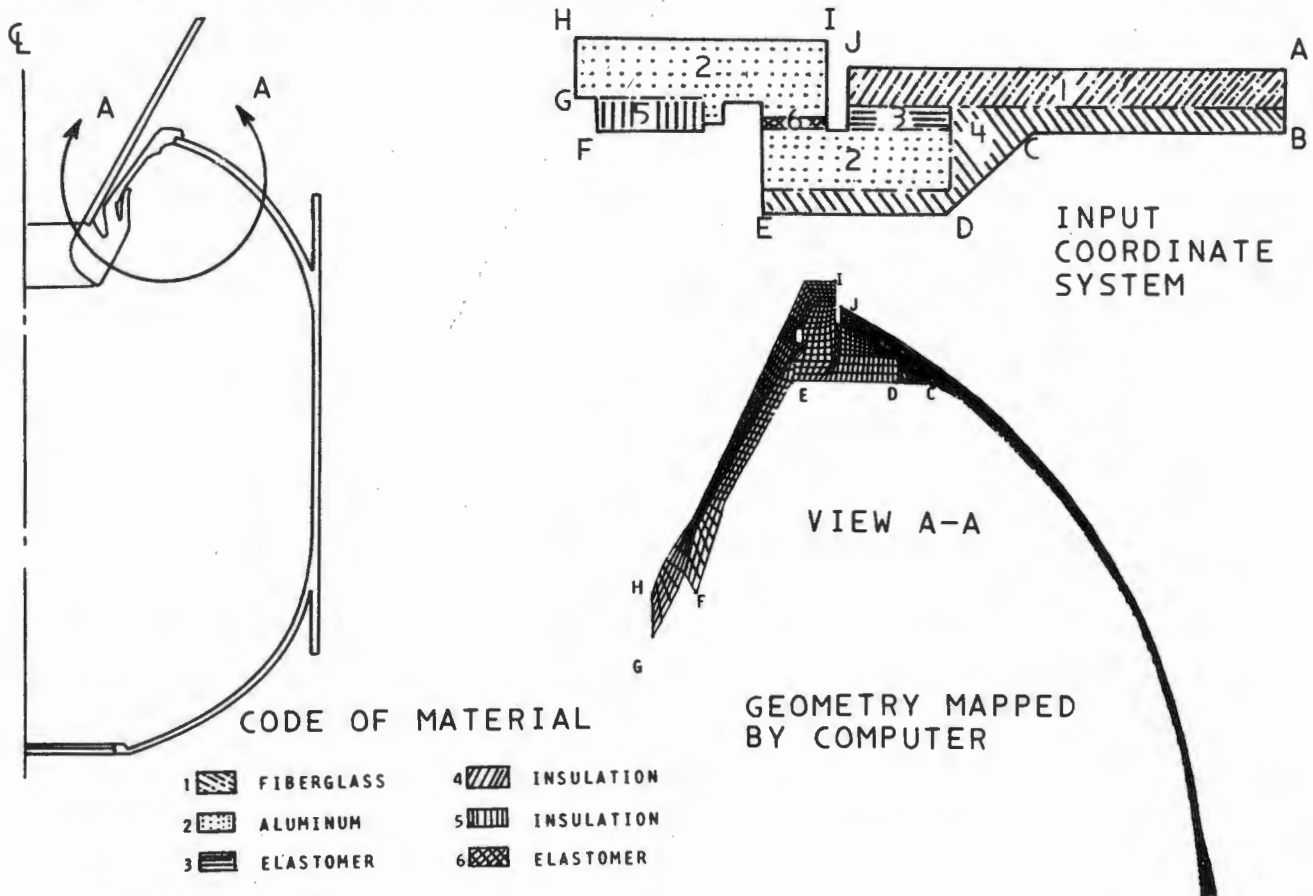


FIGURE 5
FINITE ELEMENT MODEL GENERATION

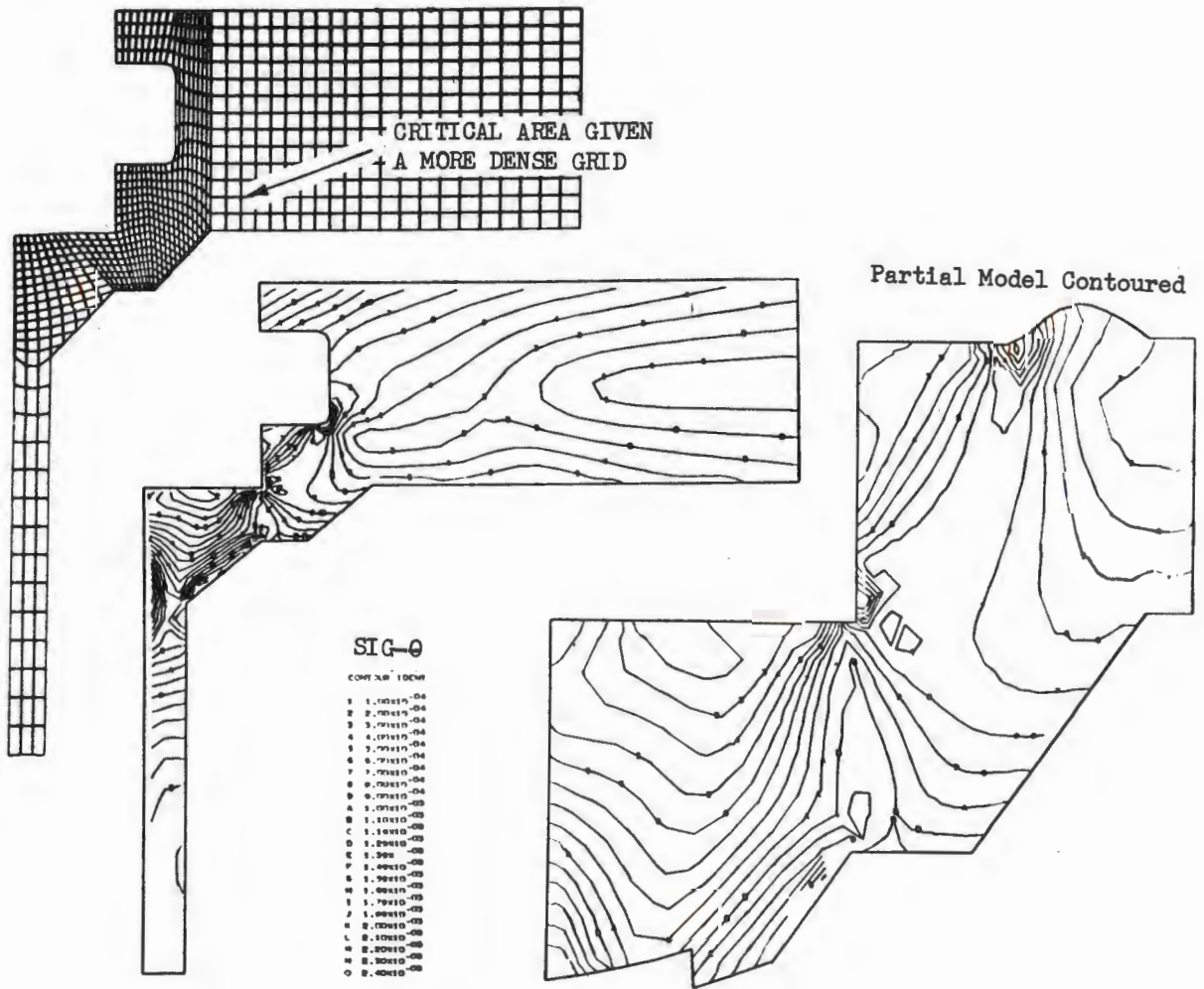


FIGURE 6
FINITE ELEMENT MESH AND RESULTANT
CONTOURS OF TANGENTIAL STRAIN

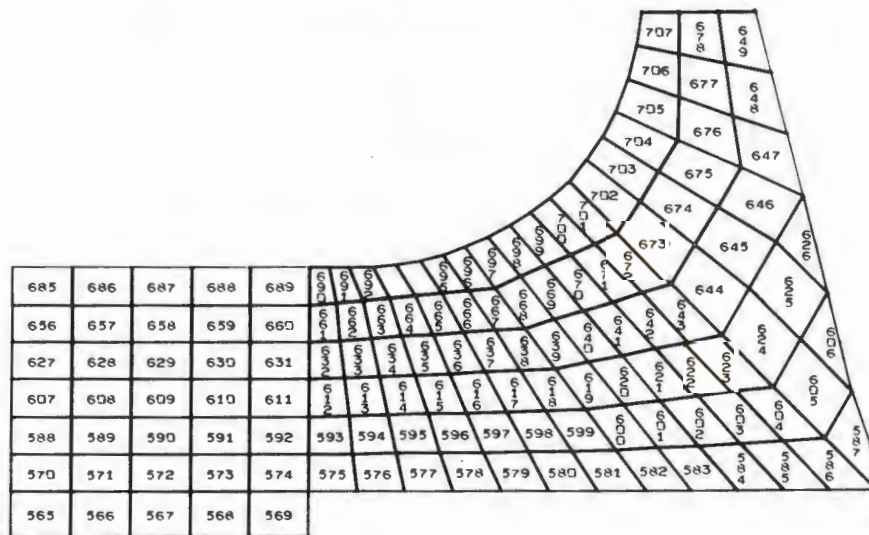


FIGURE 7
PARTIAL MODEL WITH ELEMENT NUMBERS DISPLAYED

A representation of the structure with element or nodal numbers displayed (Figure 7) is invaluable to the user when he is reducing nodal deflection data and element stress and strain outputs, or when he is attempting to detect input errors.

On symmetric structures, only a portion of the structure need be modeled for analysis, but for visualization purposes symmetric models may be "flip-flopped" to generate the entire structure (Figure 8) from a single plane of symmetry.

After the model has been analyzed the data may be reduced through the use of stress and strain cut plots (Figure 9), deflected plots (Figure 10), element state plots, contour plots, and time history plots, all of which may be output in a specific report format if desired. Deflected plots may be of the entire structure or any portion, and may show actual or magnified deflections (Figure 11). Element state plots display which elements are plastic, and which elements have been loaded and unloaded during an incremental solution. Contour plots of the full structure or any portion may be obtained with the number of contour lines being automatically selected to the desired line density (Figure 6). In the case of thermal loadings, contours of the temperature

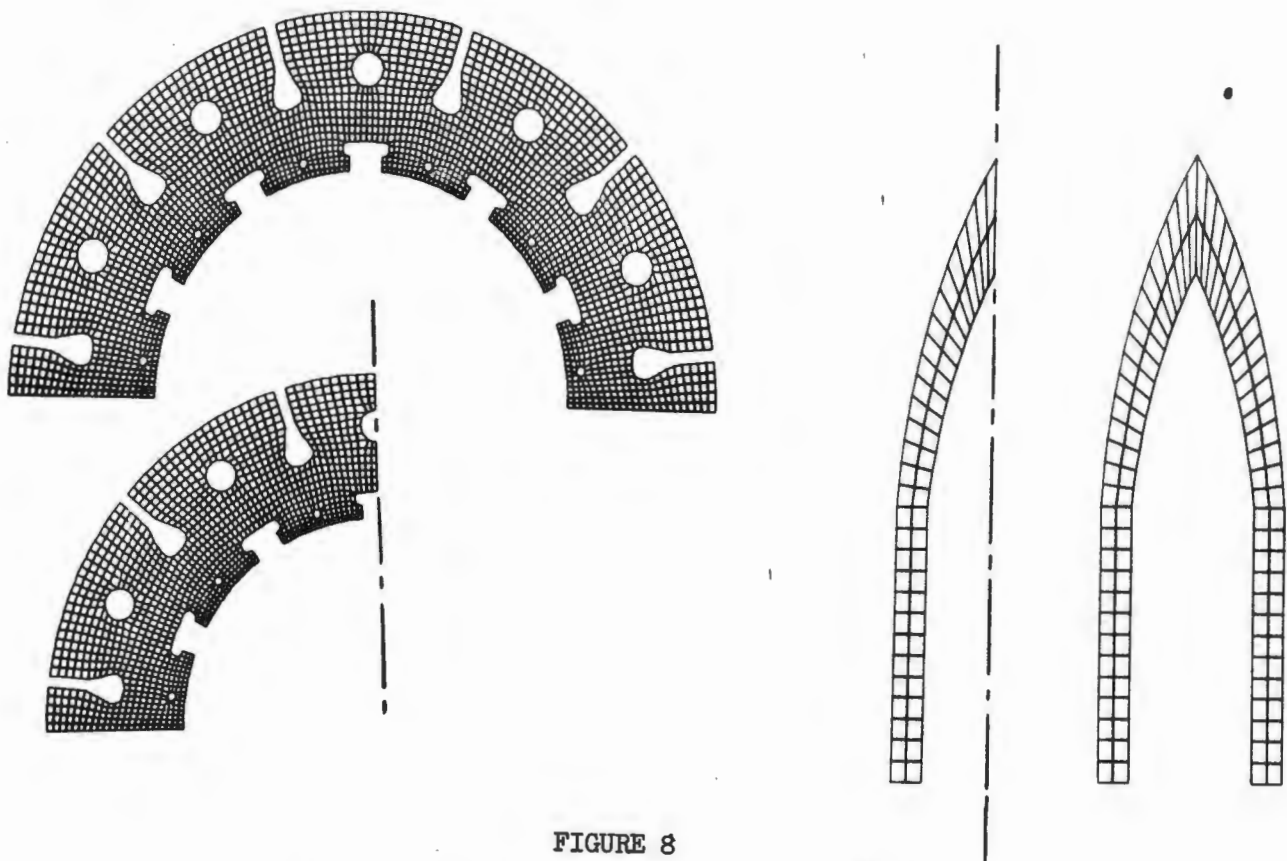


FIGURE 8

SYMMETRIC FIGURES MAY BE REVOLVED ABOUT THE AXIS OF SYMMETRY RESULTING IN A PLOT OF THE ENTIRE FIGURE

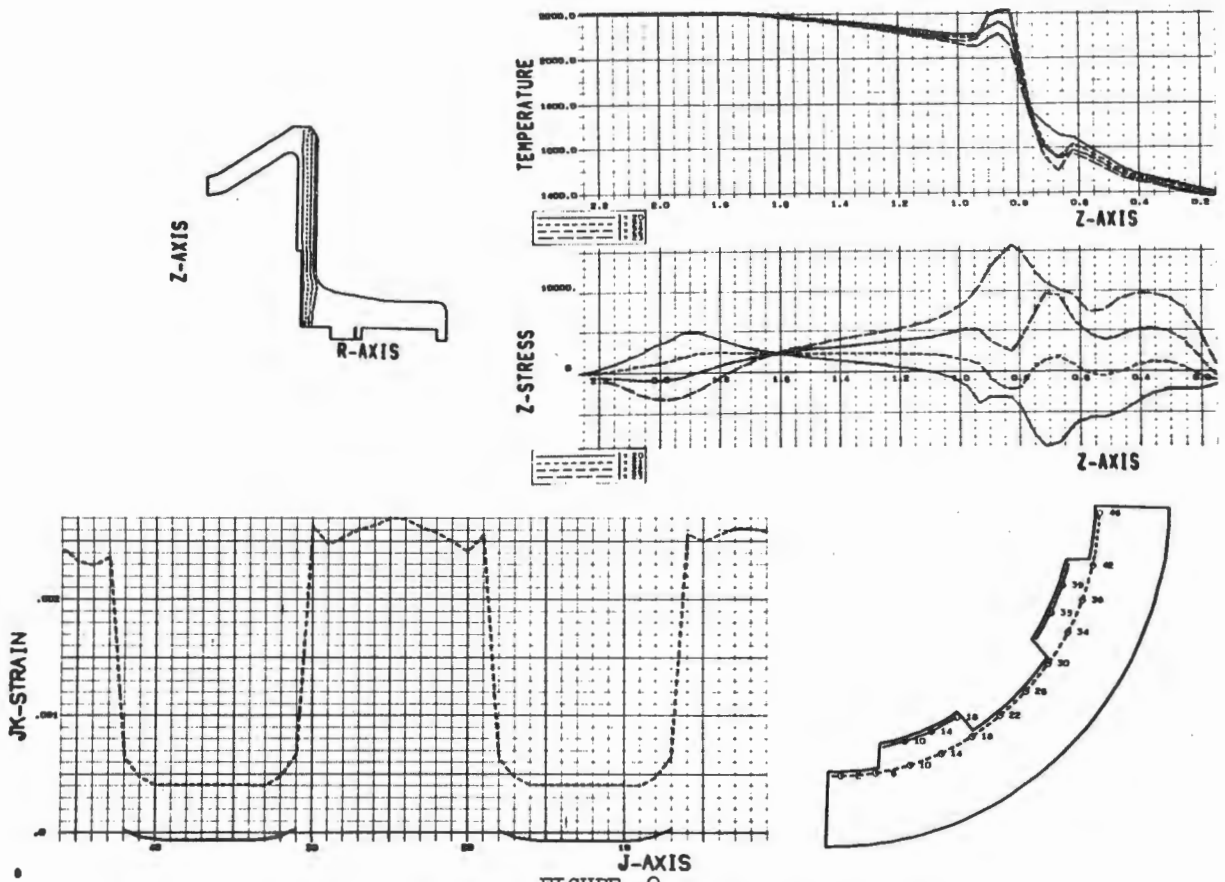


FIGURE 9
ANALYTICAL RESULTS ARE GRAPHED ALONG
ANY CUT THROUGH THE MODEL

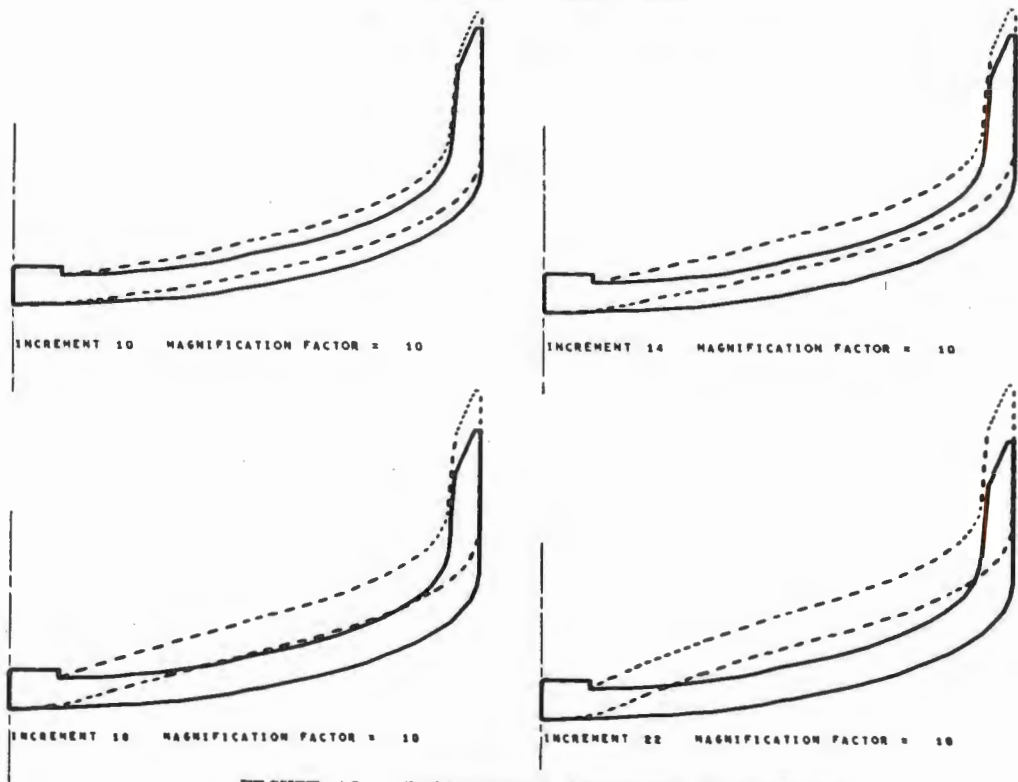


FIGURE 10 INCREMENTAL BOUNDARY DEFLECTIONS

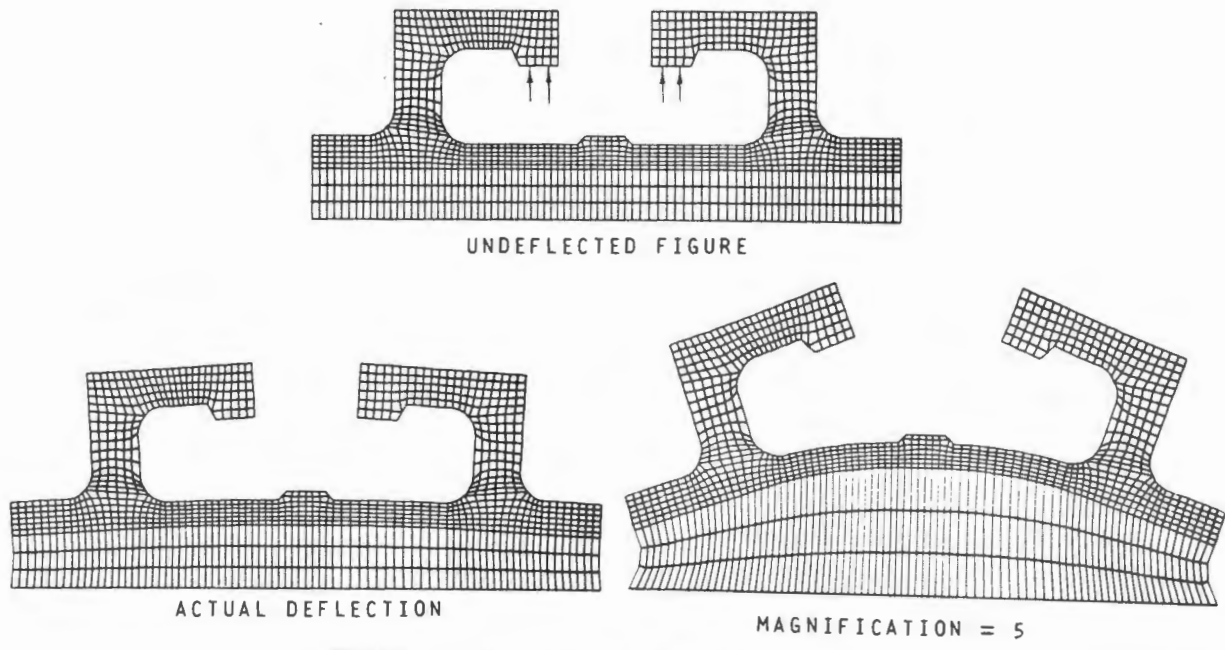
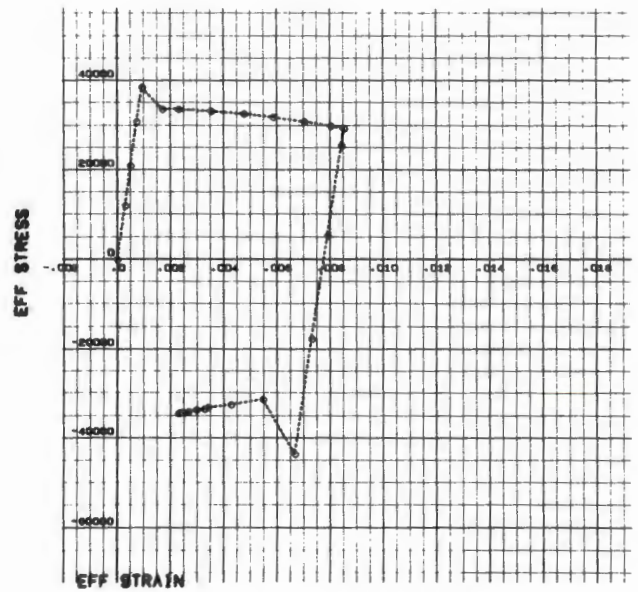
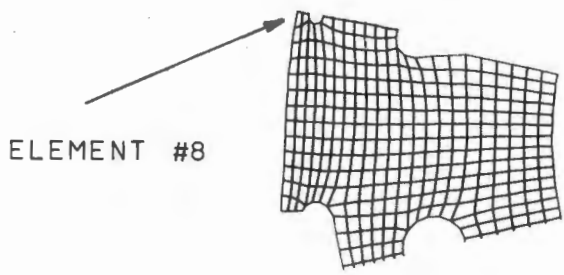
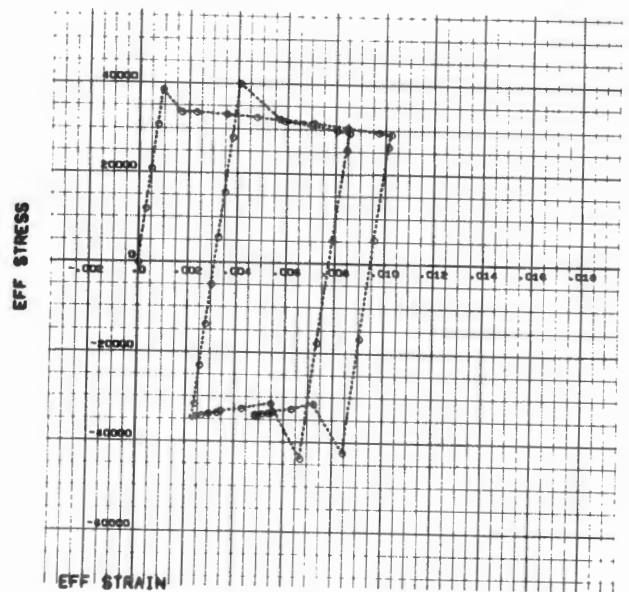


FIGURE 11 DEFLECTED FINITE ELEMENT MODEL



FIRST THERMAL CYCLE



FIRST AND SECOND CYCLE

FIGURE 12 STRESS-STRAIN HISTORY (ELEMENT #8)

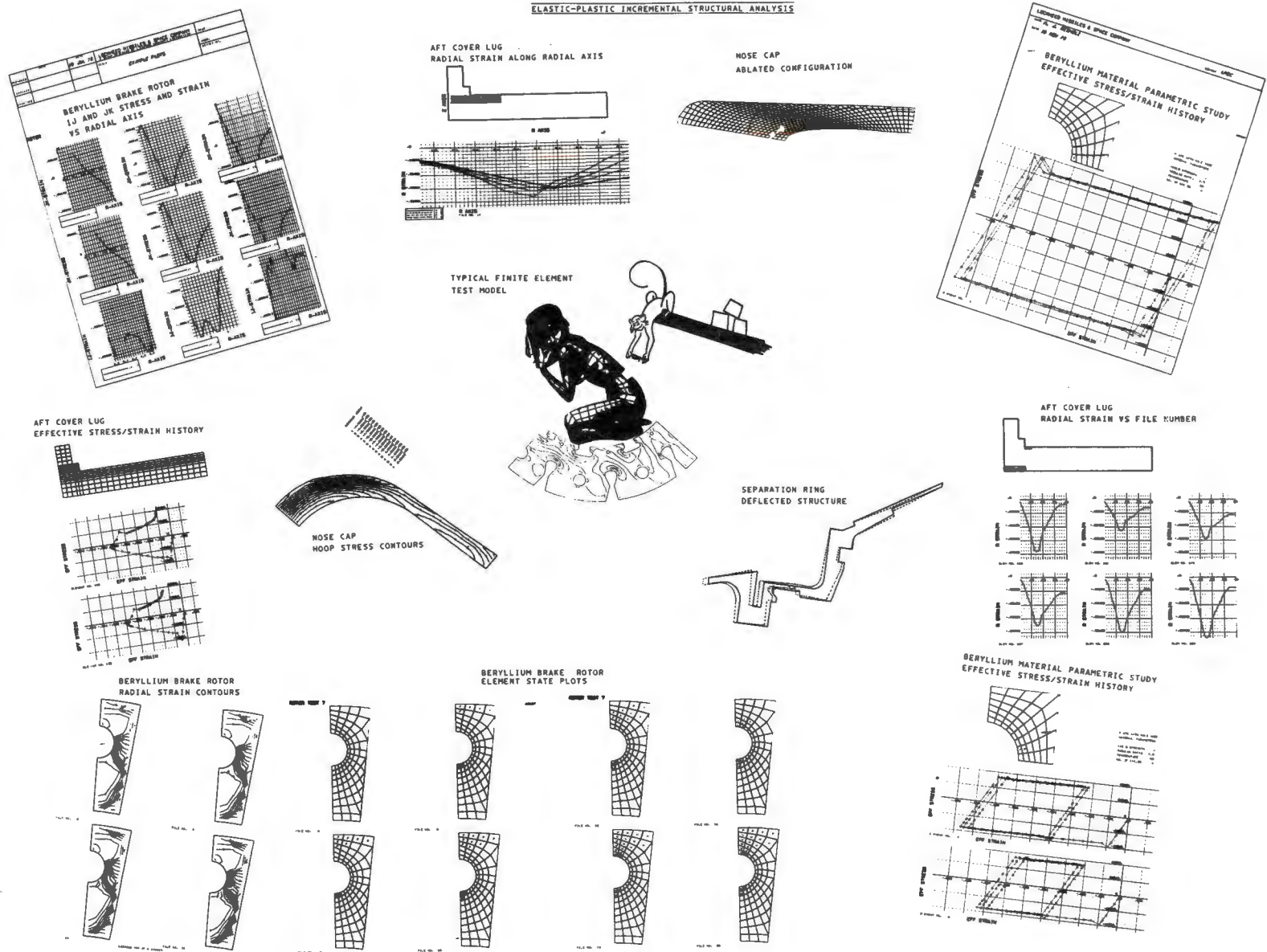


FIGURE 13
GRAPHICS PACKAGES AVAILABLE FOR
TWO-DIMENSIONAL FINITE ELEMENT MODELS

gradient applied to the structure may also be obtained. Output stresses and strains may be graphed along any cut through the structure in a variety of output modes, and in the case of incremental solutions, time history plots may be obtained showing how an element has reacted during a series of static and thermal loadings and unloadings, including plastic deformation of elements during a load increment (Figure 12). The collage presented as Figure 13 summarizes a typical graphics package currently available for two-dimensional analysis.

GRAPHICS PACKAGES FOR MIXED STRUCTURES

A mixed structure, being an assemblage of links, beams, membranes and plates, must be viewed graphically in three dimensions. A series of advanced general purpose codes in this category exists in the field of structural mechanics (References 2, 3 and 4), and these codes are capable of handling highly complex problems containing many thousands of unknowns, an example being the submarine hull launch tube model shown in Figure 14. Being three-dimensional, it is advantageous to examine the structure from a variety of viewpoints in order to clearly define a specific portion of a model in which the analyst is interested. LMSC's codes therefore have the ability to generate three orthographic views and, through a series of axes rotations, virtually any isometric view of the model. Again, as in two-dimensional packages, any portion of the structure may be expanded to clarify dense regions and similarly, element and nodal definition may be graphically represented on both partial and entire models (Figure 15).

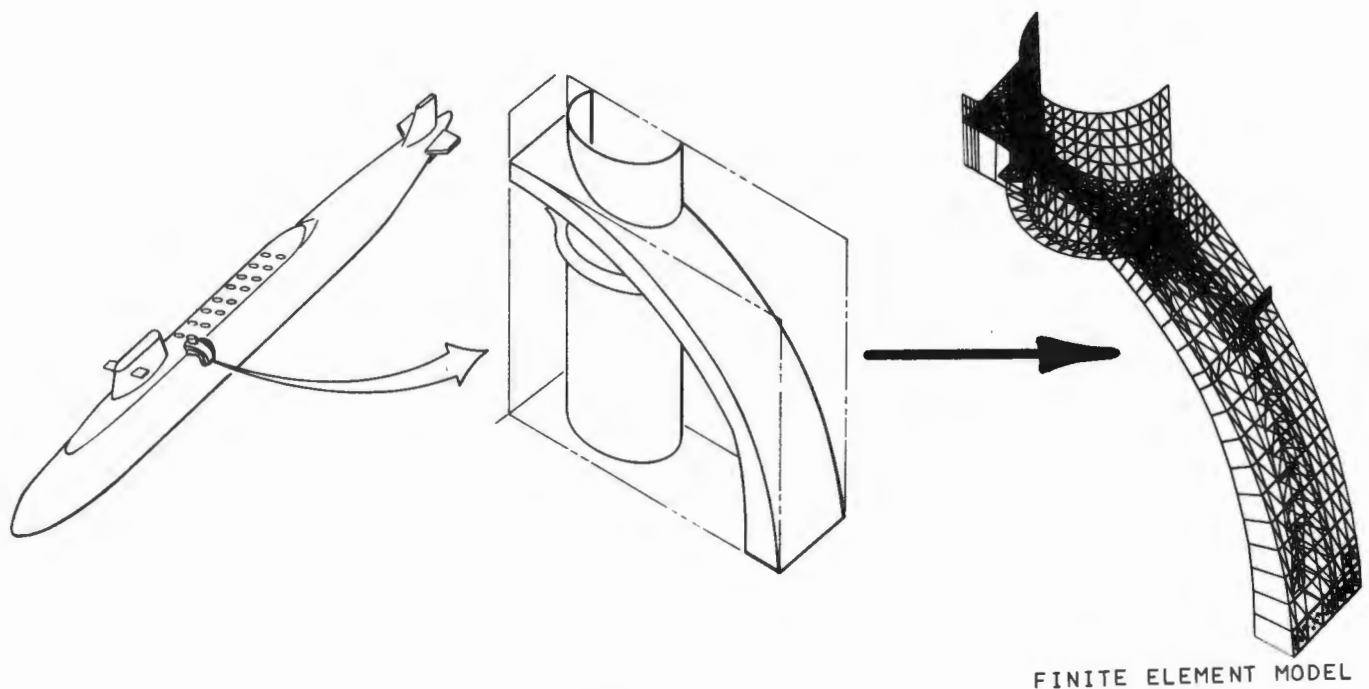


FIGURE 14
SUBMARINE HULL AND LAUNCH TUBE ANALYSIS

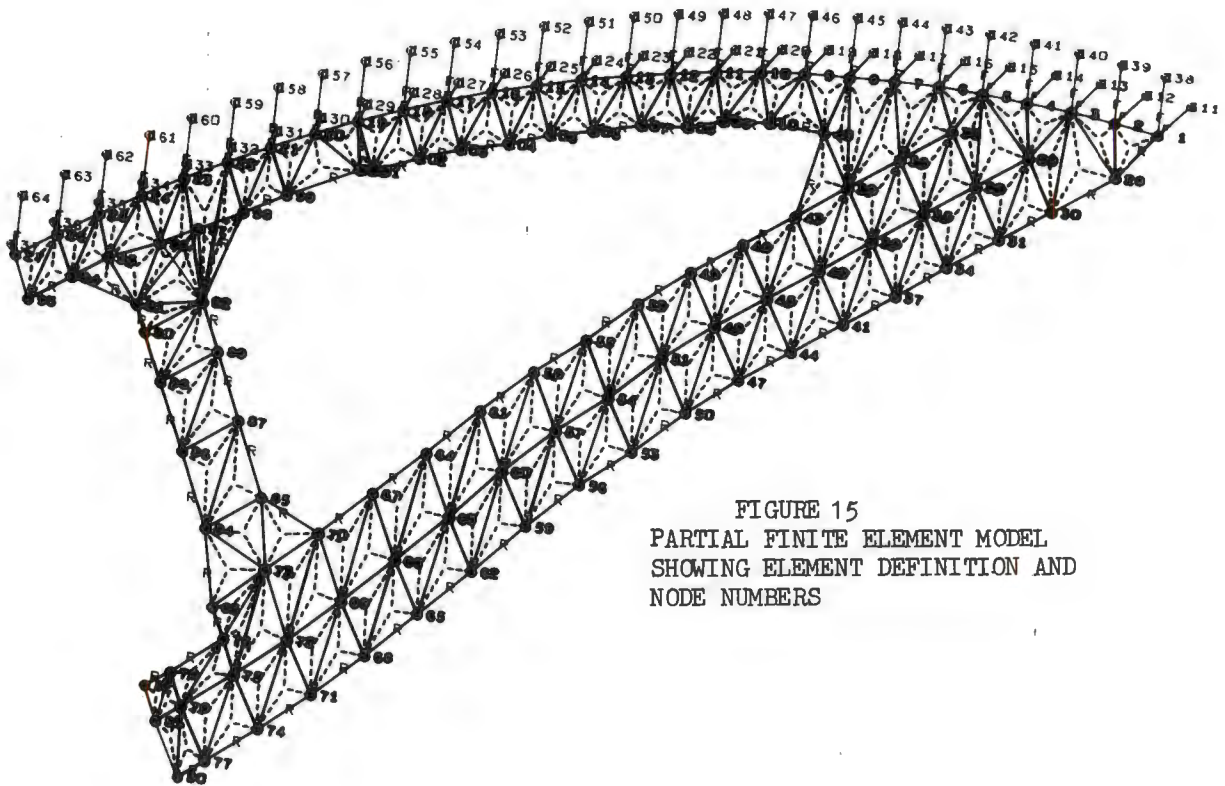
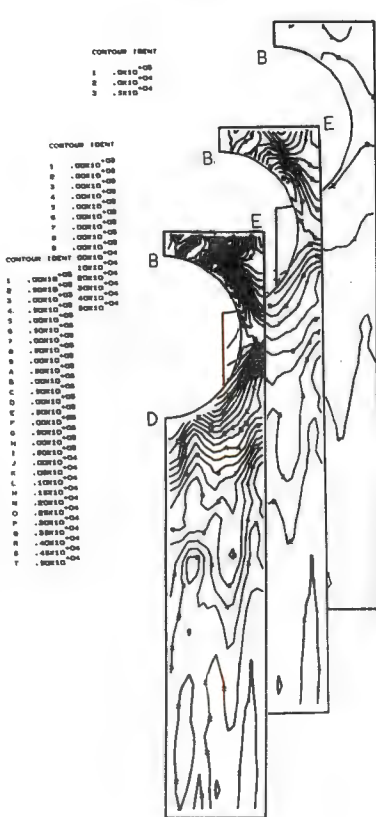
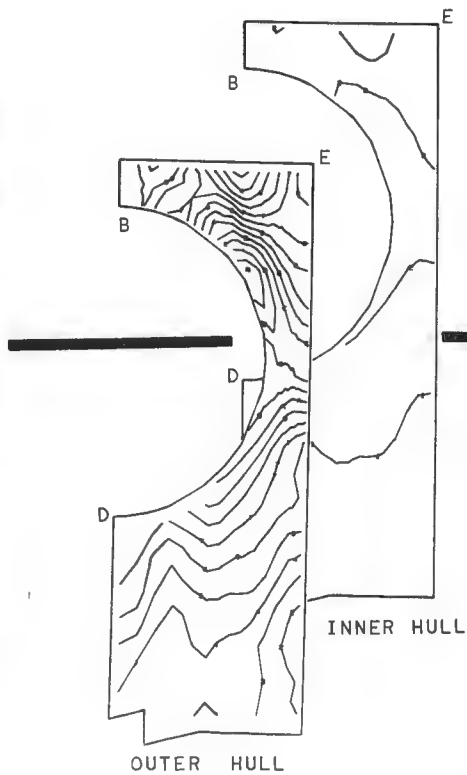


FIGURE 15
PARTIAL FINITE ELEMENT MODEL
SHOWING ELEMENT DEFINITION AND
NODE NUMBERS

UNROLLED HULL
VARIOUS DENSITIES



- CONTOUR IDENT
- 1 .00010-08
 - 2 .00010-04
 - 3 .00010-04
- CONTOUR IDENT
- 1 .00010-08
 - 2 .00010-08
 - 3 .00010-08
 - 4 .00010-08
 - 5 .00010-08
 - 6 .00010-08
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CONTOUR STRESS PLOTS
SIGMA-1

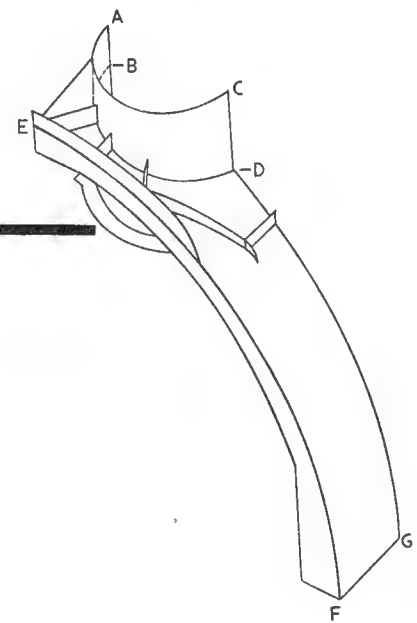
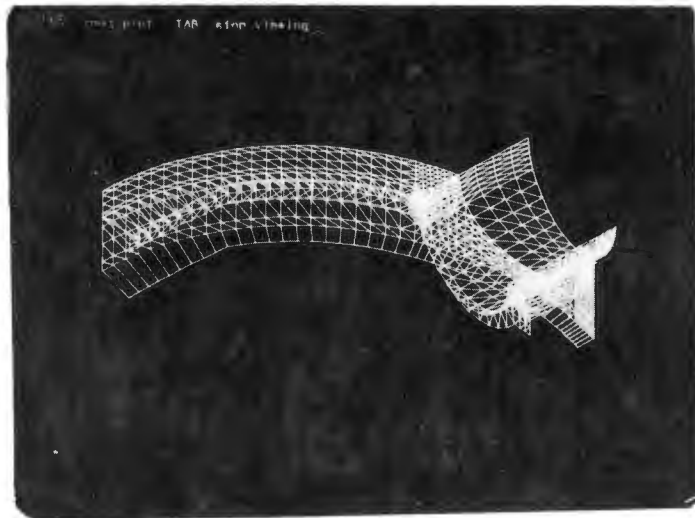


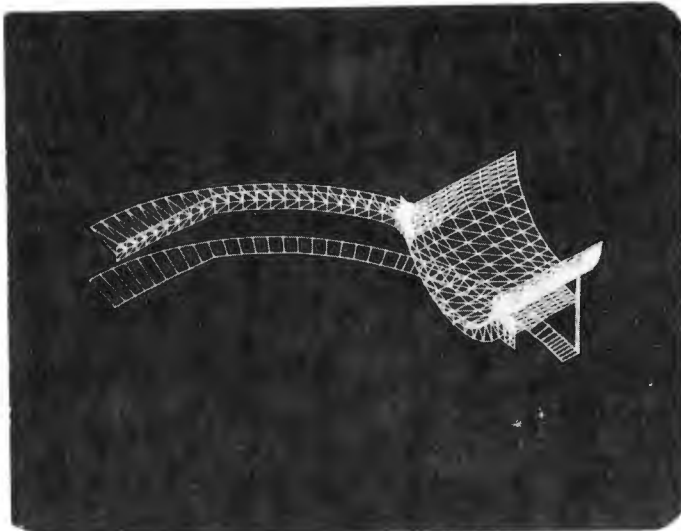
FIGURE 16
ISO-STRESS CONTOURS OF UNROLLED HULL

In mixed structures it is often necessary to overlay one element type on top of another, such as a beam along the edge of a plate, in order to approximate as closely as possible the actual structure being examined. The ability to separate each element type and plot them individually allows the user to check his model and insure its validity. The user may also generate any special combination of elements on a single plot. Thus a user can proceed with a model buildup, starting with a beam structure, next adding links, and finally generating the required number of plates and membranes. Such techniques almost eliminate the possibility of obtaining a solution containing possible hidden errors due to a faulty model.

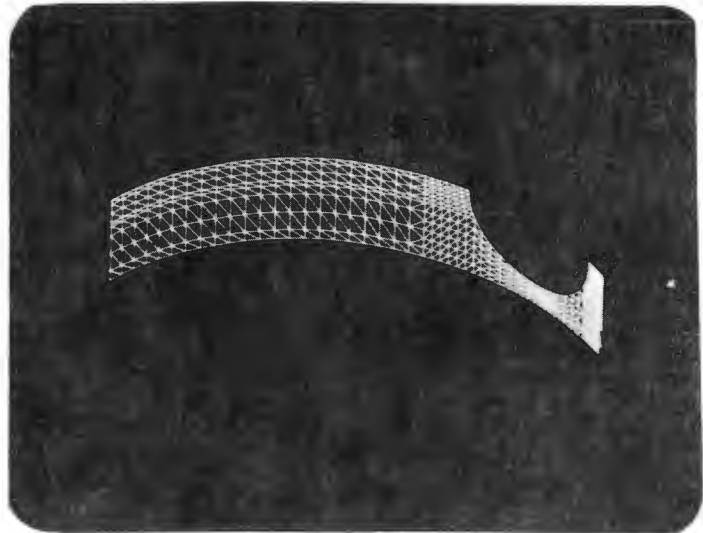
As in the case of two-dimensional analysis, models which are symmetric in nature may be "flip-flopped" to generate a larger portion of the structure, and models which are a combination of smaller components may be displayed as an exploded view giving more detail to each component individually (Figure 17).



A.
Entire Model



B. Tube and Stiffeners



C. Hull

FIGURE 17
FINITE ELEMENT MODEL AND EXPLODED PARTIALS
DISPLAYED ON AN INTERACTIVE SCOPE

Structures being modeled using bending elements can be contoured, showing stresses and strains in both the local and global coordinate systems, both inside and outside the structure (Figure 16). If the surface of the model being contoured is curved, the program unrolls the surface bringing it into two dimensions for clarity of contour patterns. Again, the density of the contour lines, the limits of the contours and the contour increment are all controlled by the user. However, the program is automated to make a "best guess" on all of these quantities, if not overridden, thus saving the user from excess work, or having to "guess" at the magnitude of resultant stresses and strains prior to initial execution. The reduction of output is again aided through the use of deflected plots showing both actual and magnified deformations of the entire structure, any partial structure, or any element type. A deflected structure may be displayed either by itself or superimposed over the original undeflected shape (Figure 18). The user may also obtain a set of stress cuts along any series of elements through the structure plotting any output quantity generated. The collages presented as Figures 19 and 20 summarize graphics packages currently available for mixed structures.

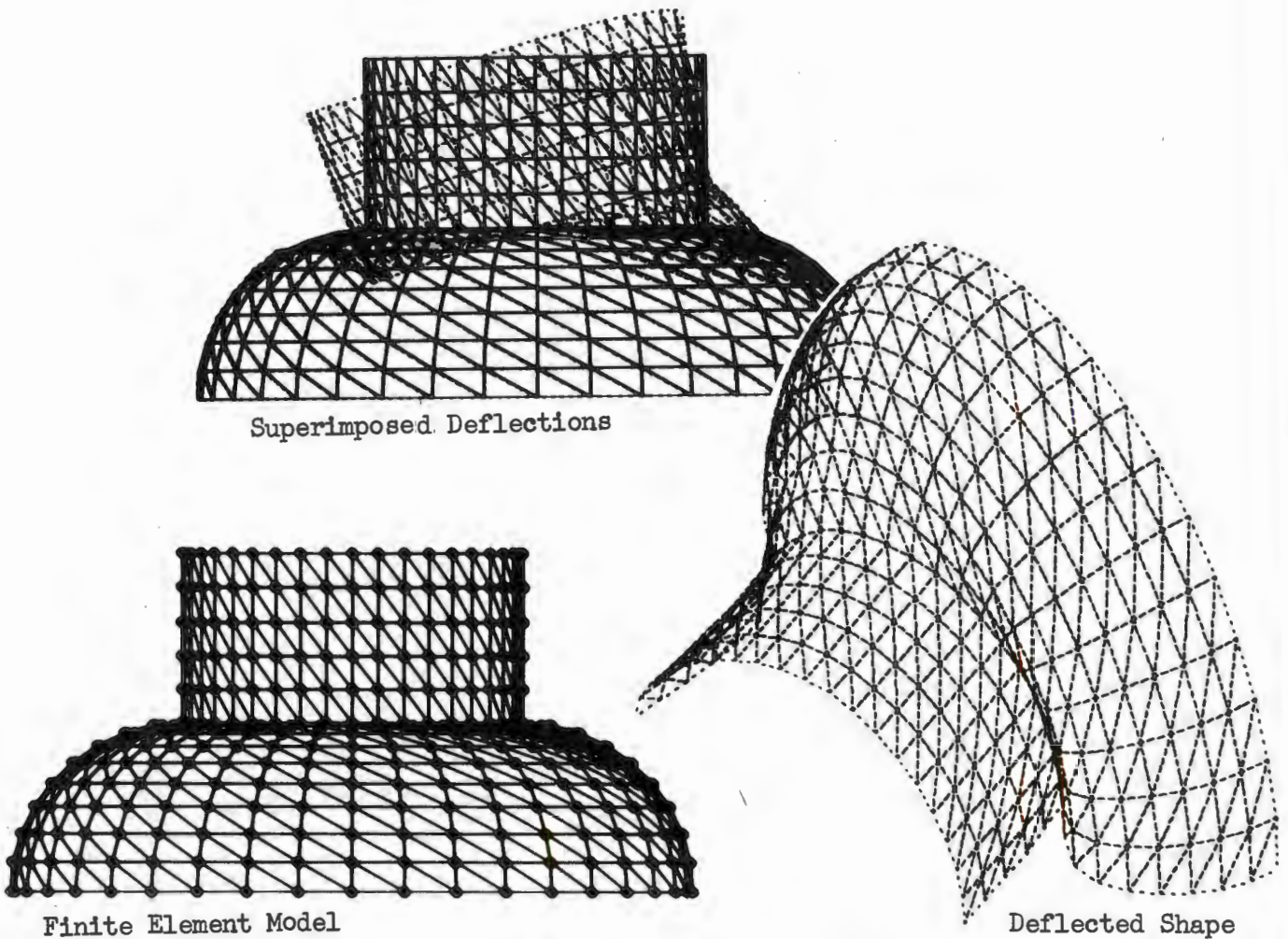
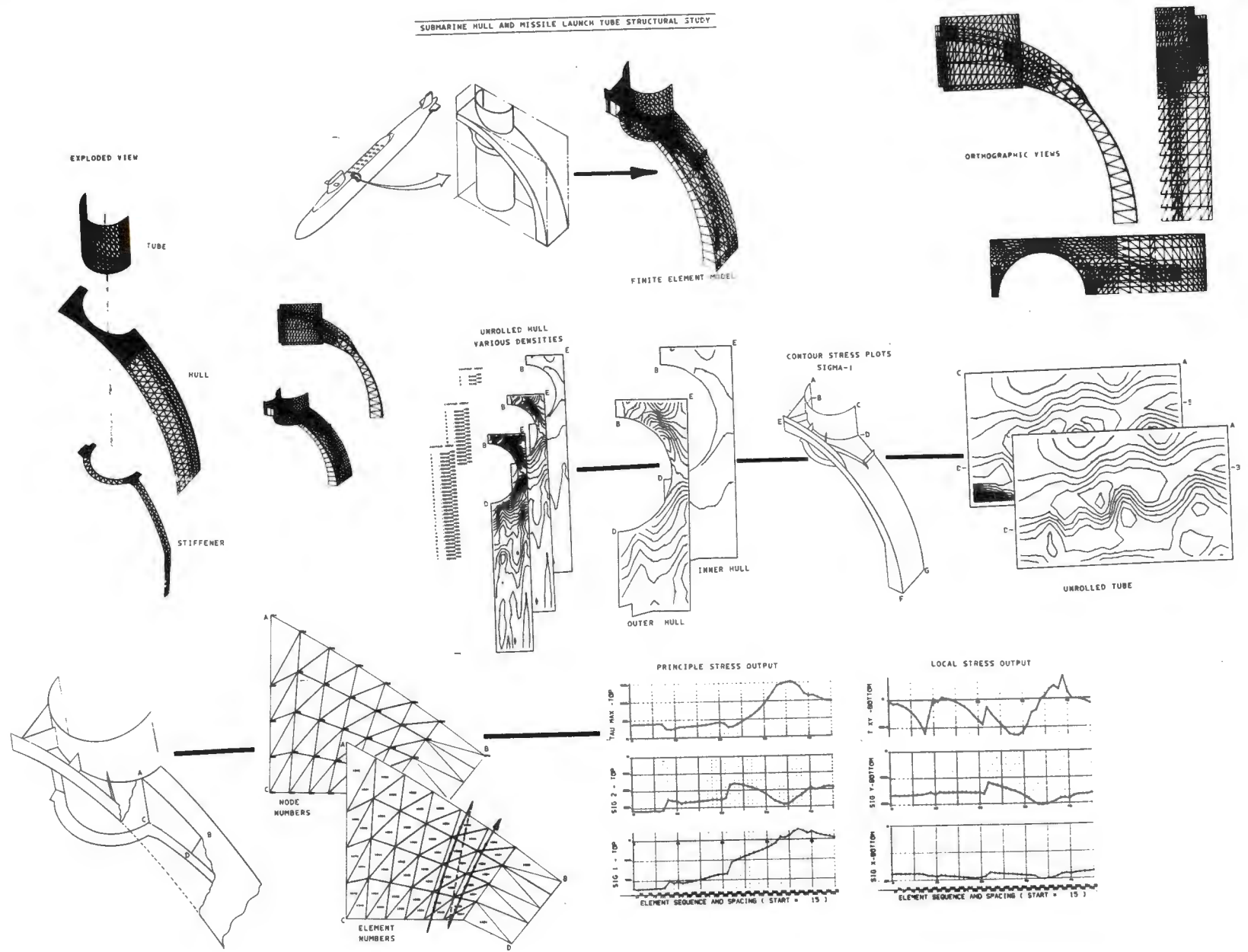


FIGURE 18

FINITE ELEMENT MODEL AND DEFLECTED
SHAPE OF PRESSURE VESSEL DOME



837

FIGURE 19
 GRAPHICS PACKAGES AVAILABLE FOR
 MIXED STRUCTURE FINITE ELEMENT MODELS

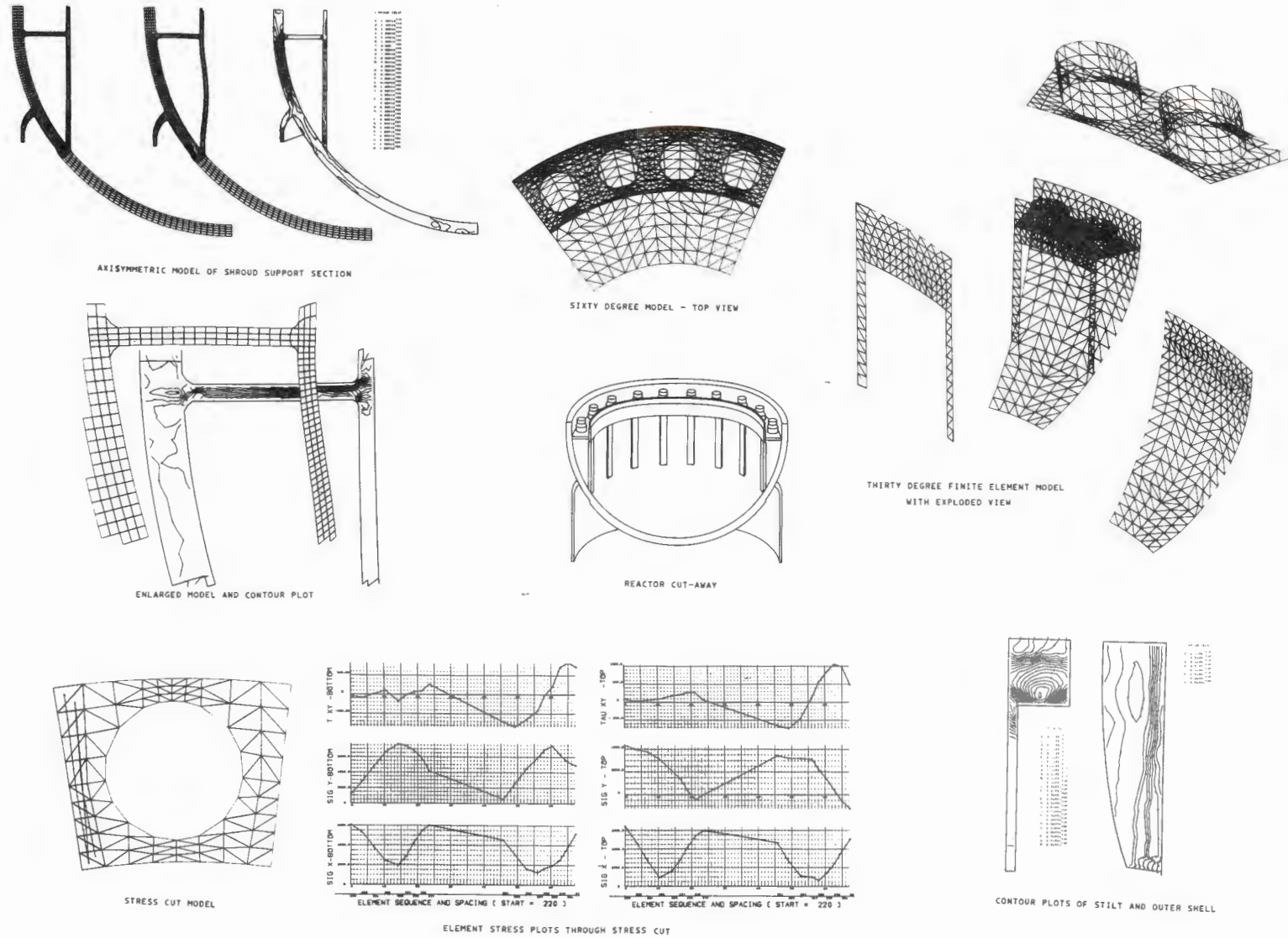


FIGURE 20
GRAPHICAL OUTPUT FOR REACTOR VESSEL ANALYSIS

GRAPHICS FOR ARBITRARY SOLIDS

The addition of solid elements into finite element codes (Reference 9) has further emphasized the need for more extensive display methods as discussed in References 10 and 11. Structures composed of such elements inherently contain large quantities of internal lines which tend to unduly complicate a plot of the entire structure (Figure 21). For purposes of clarity, packages have therefore been developed to show slices of elements or nodes (Figure 22) distinct from the rest of the model, with or without element and node definitions (Figure 23), with each slice being able to be rotated to any desired viewing angle. Similarly, deflected plots of portions of the structure may be displayed showing actual or magnified deflections. Such deflected figures can be displayed individually or superimposed over the undeflected structure (Figure 24). The viewer can, therefore, display any block of elements, any plane of elements through the structure, or any surface of elements. Further graphical displays allow stress and strain cuts through the structure and plotting output quantities for any element faces in addition to element centroids. Defining the stress cut visually is greatly aided by displaying the elements being graphed in reference to a plane of nodes, thus orienting the stress cut within the entire model as shown in Figure 25.

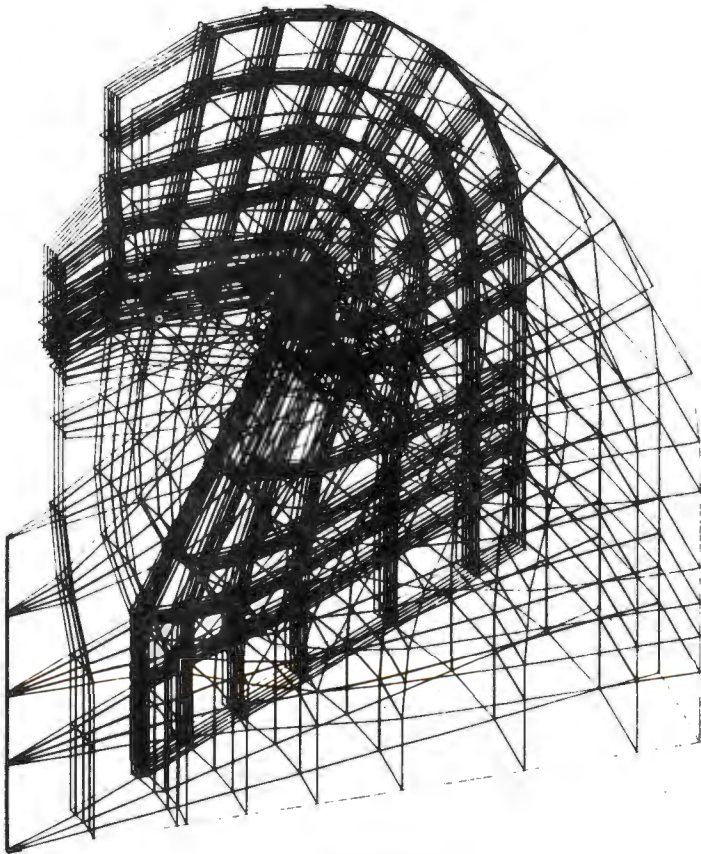


FIGURE 21
ENTIRE SOLID FINITE ELEMENT MODEL

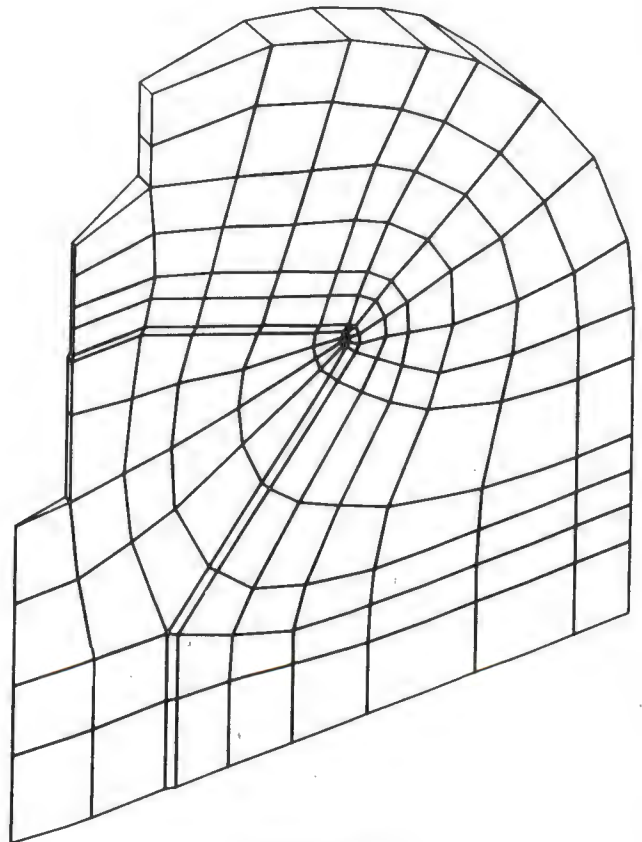


FIGURE 22
SINGLE LAYER OF ELEMENTS

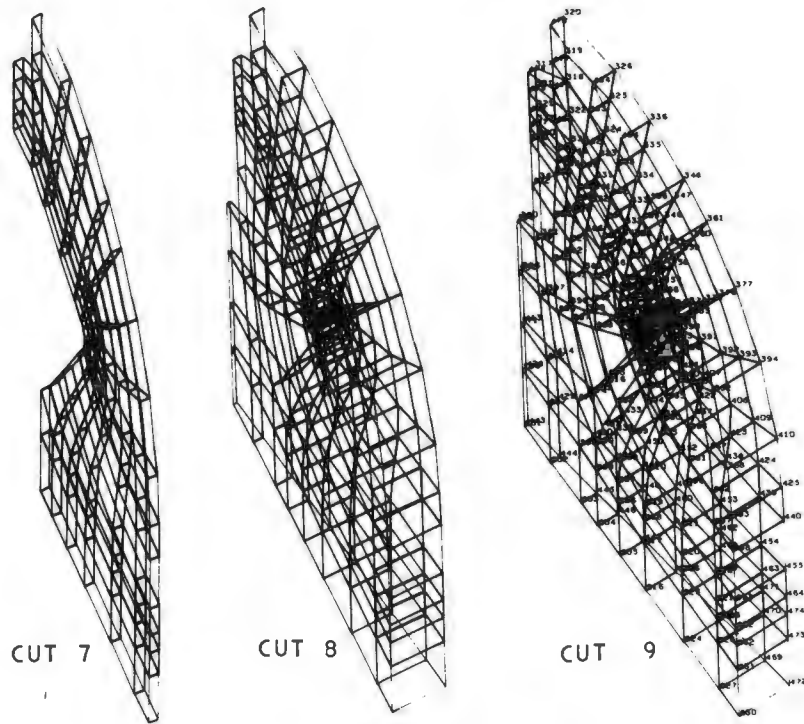
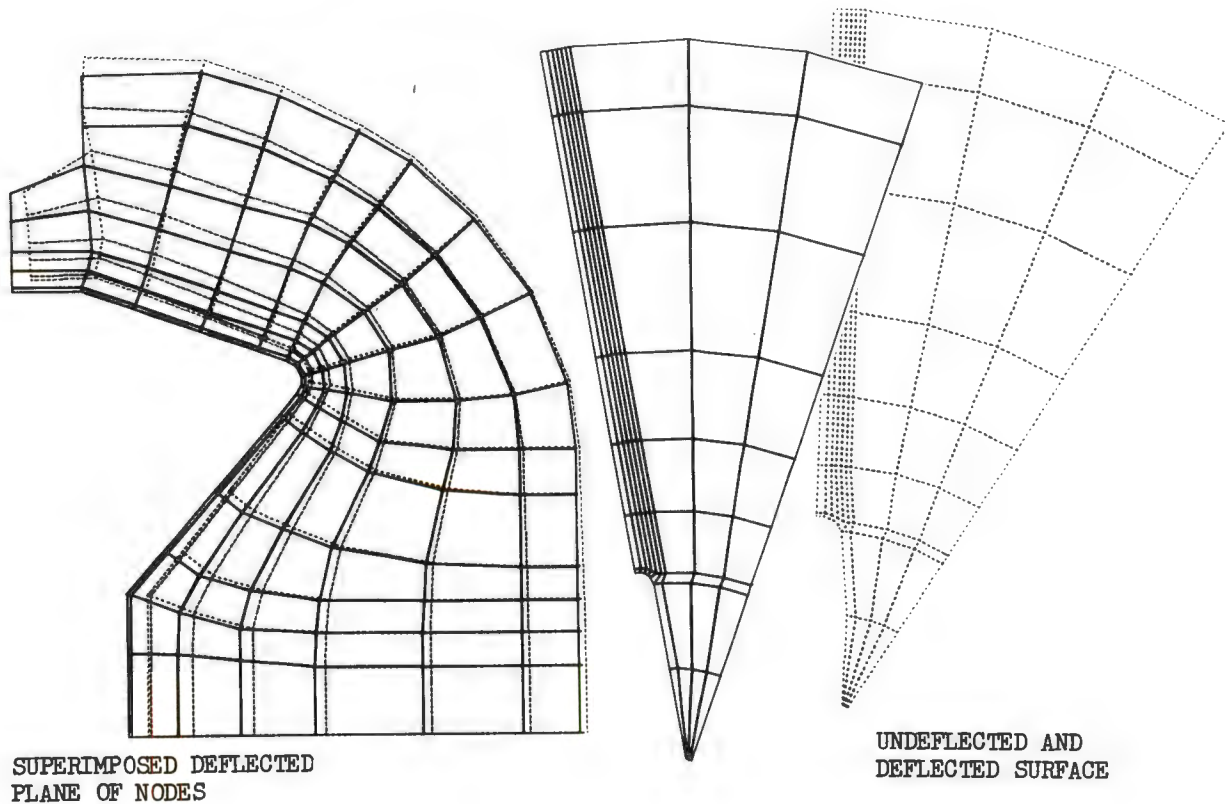


FIGURE 23
 PARTIAL MODEL SHOWING SINGLE
 PLANE OF ELEMENTS



SUPERIMPOSED DEFLECTED
 PLANE OF NODES

UNDEFLECTED AND
 DEFLECTED SURFACE

FIGURE 24
 DEFLECTED STRUCTURES FOR ARBITRARY SOLIDS
 840

STRESS CUT NO. 30

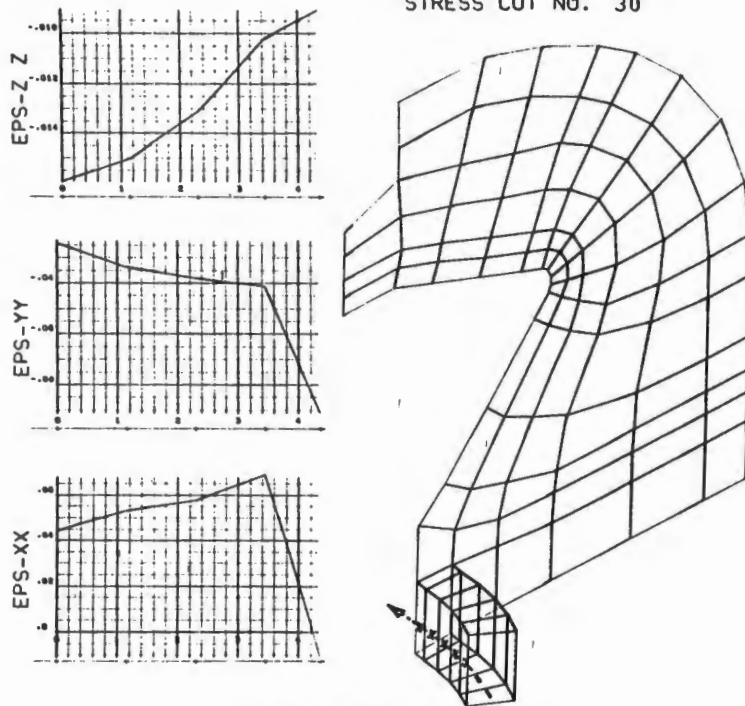
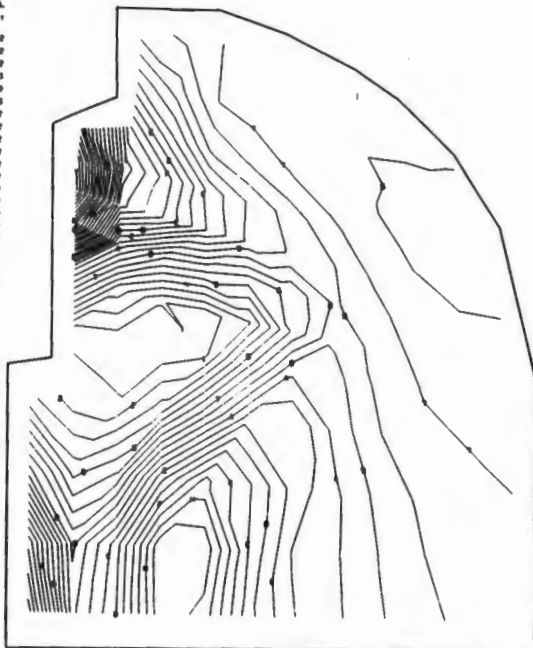


FIGURE 25
OUTPUT STRESSES AND STRAINS ARE GRAPHED
ALONG ANY SERIES OF ELEMENTS

EPS-XX

- CONTOUR IDENT
- 1 -2.00E-02
 - 2 -1.50E-02
 - 3 -1.00E-02
 - 4 -5.00E-03
 - 5 -1.70E-03
 - 6 0.00E+00
 - 7 1.00E-02
 - 8 1.40E-02
 - 9 2.00E-02
 - 10 2.50E-02
 - 11 3.00E-02
 - 12 3.50E-02
 - 13 4.00E-02
 - 14 5.00E-02
 - 15 6.00E-02
 - 16 7.00E-02
 - 17 8.00E-02
 - 18 9.00E-02
 - 19 1.00E-01
 - 20 1.20E-01
 - 21 1.50E-01
 - 22 2.00E-01
 - 23 2.50E-01
 - 24 3.00E-01
 - 25 3.50E-01
 - 26 4.00E-01
 - 27 4.50E-01
 - 28 5.00E-01



EPS-ZZ

- CONTOUR IDENT
- 1 0.00E+00
 - 2 1.00E-02
 - 3 1.50E-02
 - 4 2.00E-02
 - 5 2.50E-02
 - 6 3.00E-02
 - 7 3.50E-02
 - 8 4.00E-02
 - 9 4.50E-02
 - 10 5.00E-02
 - 11 5.50E-02
 - 12 6.00E-02
 - 13 6.50E-02
 - 14 7.00E-02
 - 15 7.50E-02
 - 16 8.00E-02
 - 17 8.50E-02
 - 18 9.00E-02
 - 19 1.00E-01
 - 20 1.20E-01
 - 21 1.50E-01
 - 22 2.00E-01
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 - 26 4.00E-01
 - 27 4.50E-01
 - 28 5.00E-01

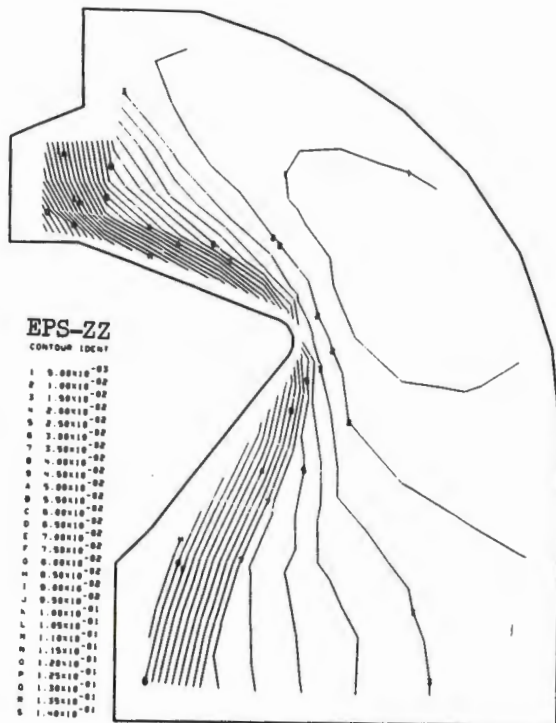


FIGURE 26
OUTPUT STRESSES AND STRAINS ARE CONTOURED
FOR A GIVEN PLANE OF ELEMENT FACES

Contour plotting in three dimensional structures can be performed on any surface of the model or on any planar slice of element faces through the model (Figure 26). In any view, output quantities for element faces as well as element centroids may be contoured to any desired degree of density.

The problem of generating a picture with hidden lines removed for any arbitrary three-dimensional structure has been solved using several different methods (References 12, 13 and 14), but the computer time and cost of generating such a picture for a structure made up of over 1900 nodes and 6300 planar surfaces cannot always be justified by the value of the final output plot. This problem is one of current interest and hidden line programs are now being tested, optimized and incorporated into both interactive and non-interactive production codes. However, through the use of graphics packages already existing in production codes the user can quickly generate a "pseudo" hidden line picture by displaying only a portion of the total model's element faces and edges (Figure 27).

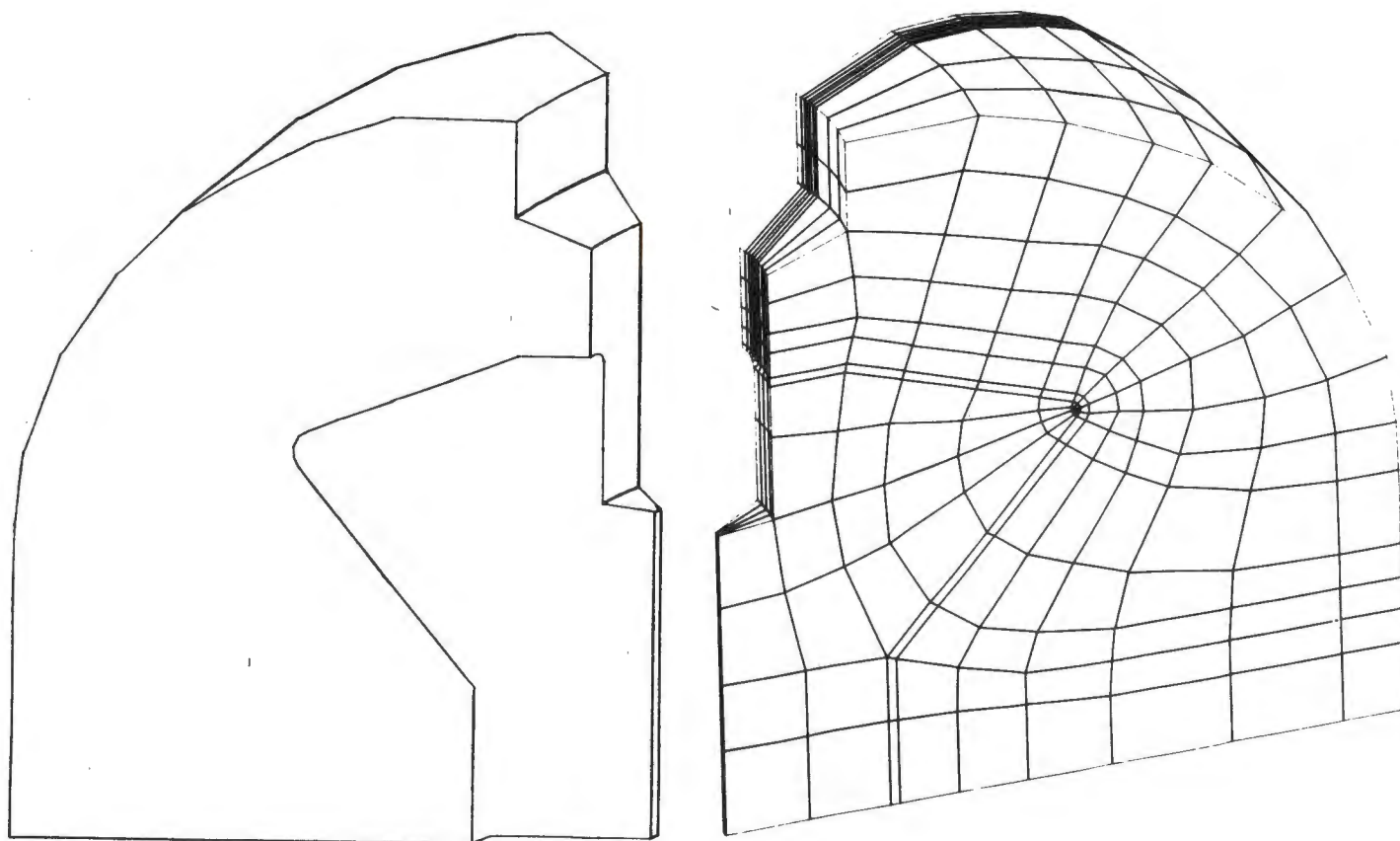


FIGURE 27

'PSEUDO'HIDDEN LINE PICTURES

SECTION III

INTERACTIVE GRAPHICS

INTERACTIVE HARDWARE

Interactive computer graphics, employing a cathode-ray-tube display terminal attached to a digital computer (Figure 28), allows the user to communicate with, and control the flow of, his own program in real time. The development of interactive graphics from a research analyst's aid to a production analysis tool has enabled the engineer to radically reduce the time span and overall cost of a given task from the levels previously required in a batch process mode. The magnitude of this savings is illustrated in Figure 29. The time necessary for a series of computer runs submitted under a batch processing mode is, of course, highly dependent on the job turnaround time of the system. Hence, while input tasks and model debugging may take days under the batch system, the same series of jobs can be completed during a single session at an interactive scope.



FIGURE 28
COMPUTEK 400 INTERACTIVE GRAPHICS TERMINAL

The heart of the interactive graphics system currently in use at LMSC is the Computek Series 400 Interactive Graphics Terminal (Reference 15) which is direct-coupled with a CDC 6400 Digital Computer and complimented by an on-line hard copy generator, joystick, digital graphics tablet, and DIS211 scope (Figure 29). The Computek is a storage tube type display retaining information it has received, as opposed to refreshed CRTs such as the IBM 2250 and the CDC 274 which are updated about 30 times per second from a memory device. Although response time is slower on a storage tube and partial screen erasing is not possible, this type of display is an order of magnitude less expensive than the refreshed type tube, while, at the same time, being more than sufficient to handle the size and type of work necessary to accompany very large finite element codes (Reference 12). In structural analysis the interactive scope is currently used to debug finite element models prior to problem solution and also as a means for selective data reduction at task completion. The solution of the problem, however, can be run on any machine, thus eliminating any machine dependence on the computer to which the CRT is coupled. It has been shown to be economically advantageous to do interactive model debugging on a smaller inexpensive computer in a time-sharing mode, subsequently running the computer model for analysis results on a machine with large core memory and mass storage devices which can handle the size and complexities of a model containing more than 6500 unknowns and finally returning to the smaller interactive computer with analysis results for data reduction and report preparation.

INTERACTIVE METHODS

The Computek, as a time-sharing terminal, allows the user to substantially compress the time scale required to accomplish a particular analysis goal due to improved response time over conventional batch processing techniques.

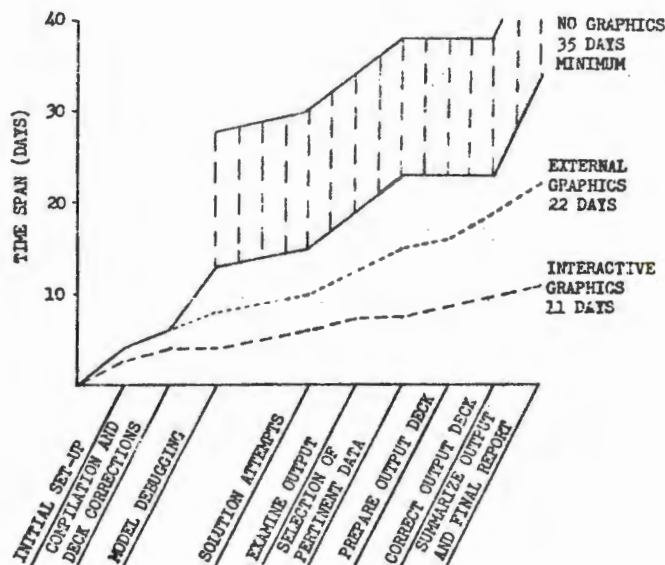


FIGURE 29
USING GRAPHICS TO REDUCE TASK TIME SPAN

In the preprocessing mode, an initial finite element model is generated using modular programming techniques and data input cards. This data is passed to the display program. The engineer, sitting at the scope terminal, has a variety of options available to him to alter and debug his model. Hence, he can display his model wholly or partially in any given view, add new nodal points and elements, change existing data, display on the screen any of the storage tables generated, and finally, recycle using these modifications to generate a corrected model (Figure 31). This pattern is repeated until the model is completely debugged, then a card deck is punched containing the model definition in a compressed form, and this punched output is fed to a larger computer to obtain analytical results. Interactive programs are currently being developed which would allow the user to reduce these results through the use of deflected pictures, output graphs, and contour plots, and thus generate a final analytical report in real time and by total reliance on computer graphics packages.

At any time during the interactive mode the user can obtain a hard copy print of the contents of the Computek screen, or store this data on a tape in a format accepted by the SC4020 and FR80 external plotters in order to obtain copies with a higher degree of resolution. Just as output from the Computek can be displayed by an FR80, so also can a tape generated for the FR80 be displayed on the Computek giving the user the ability to edit and delete results before final processing.

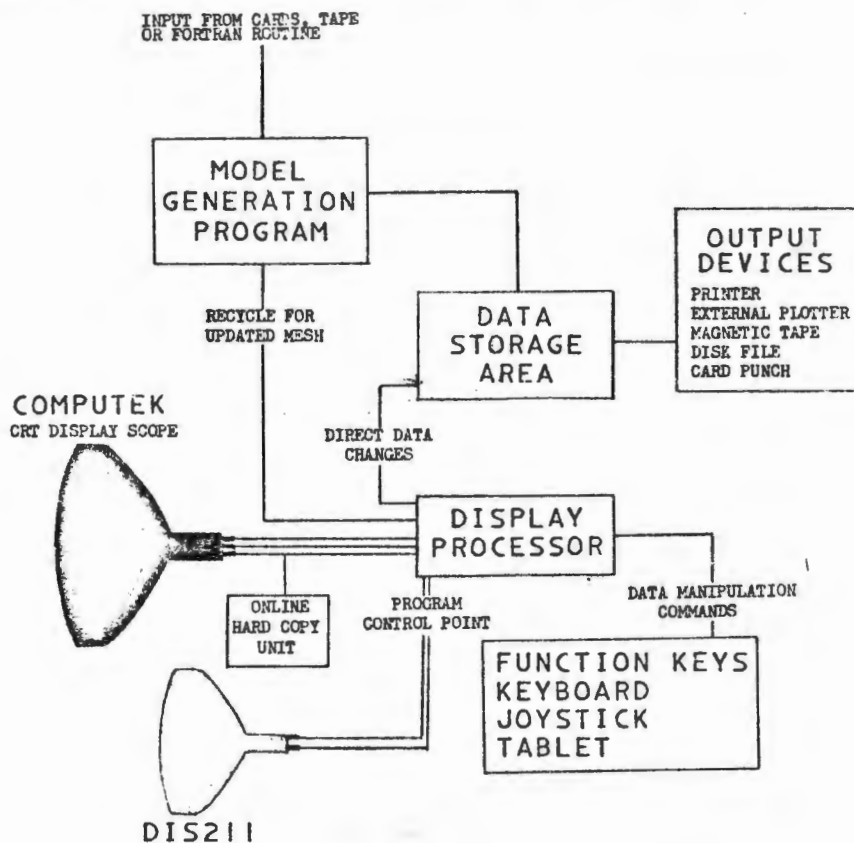


FIGURE 30
INTERACTIVE PROGRAM DISPLAY SYSTEM

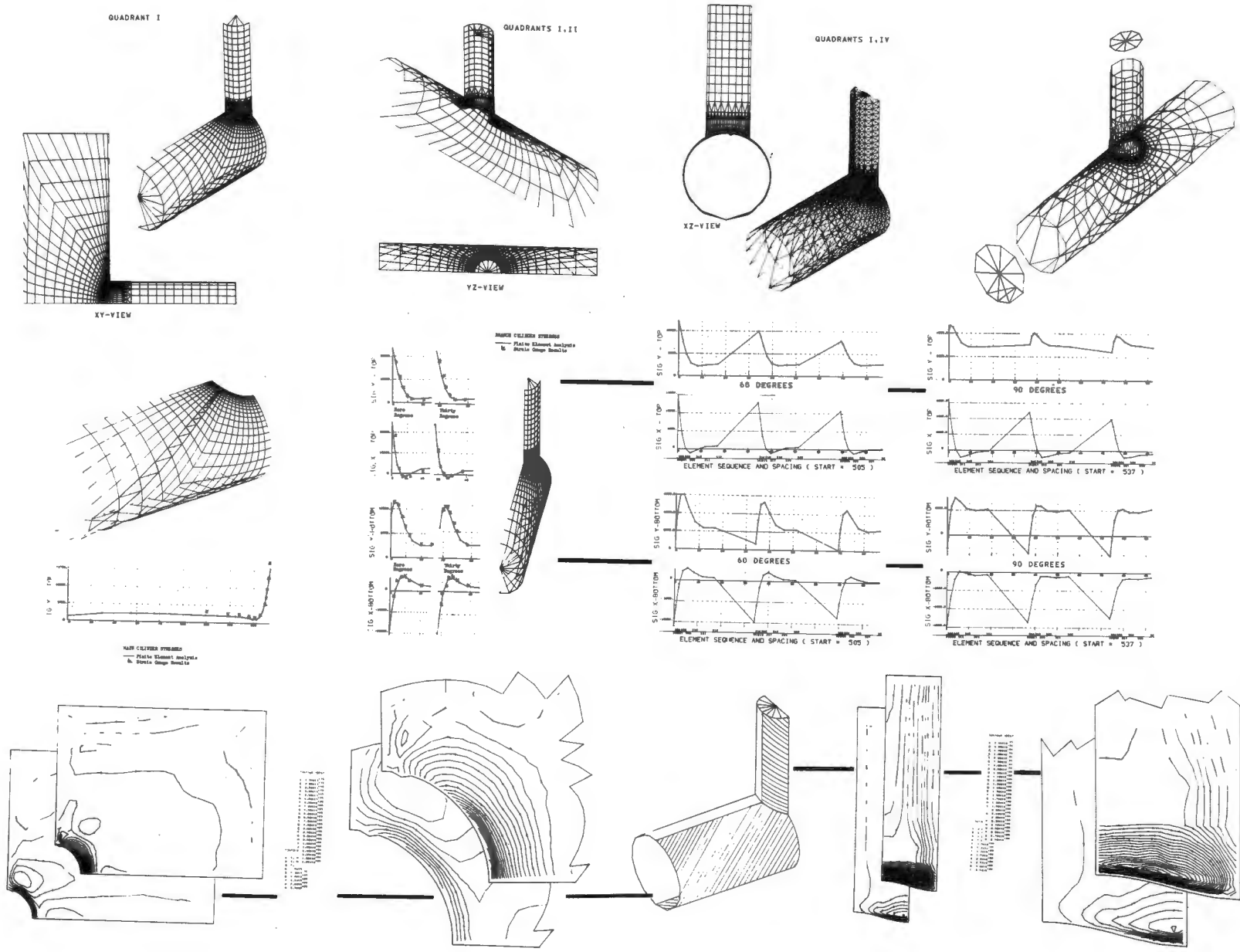
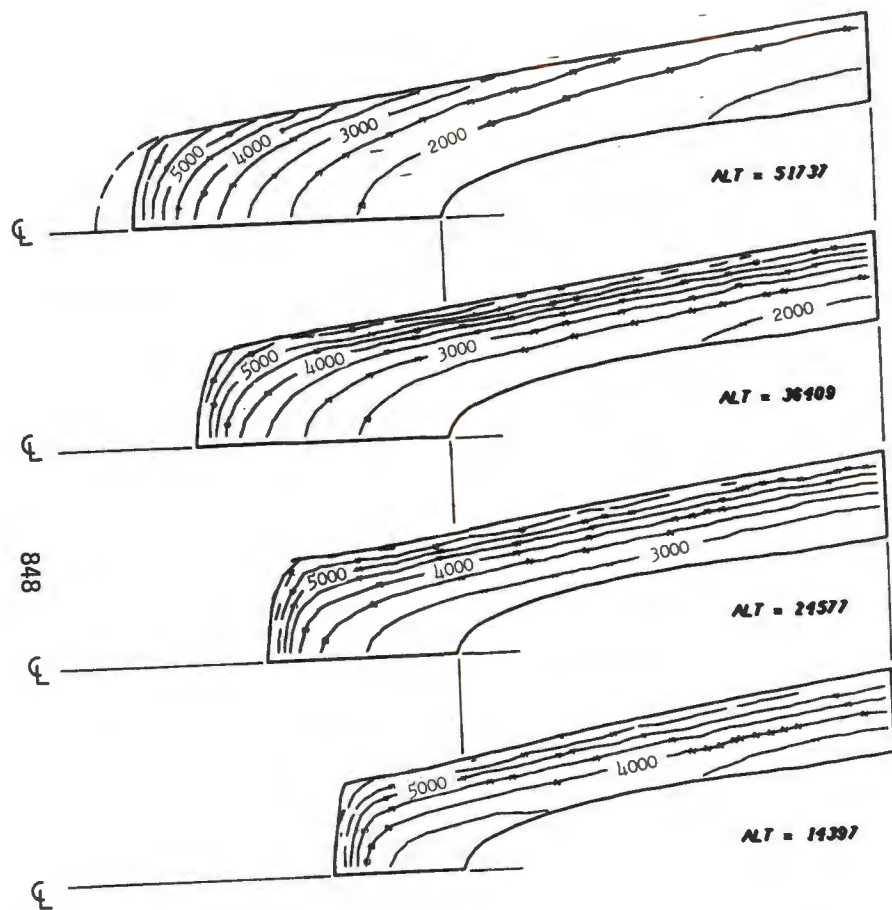
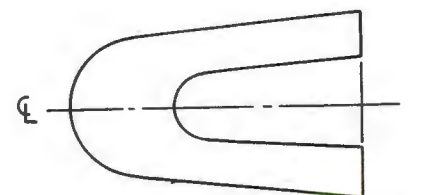


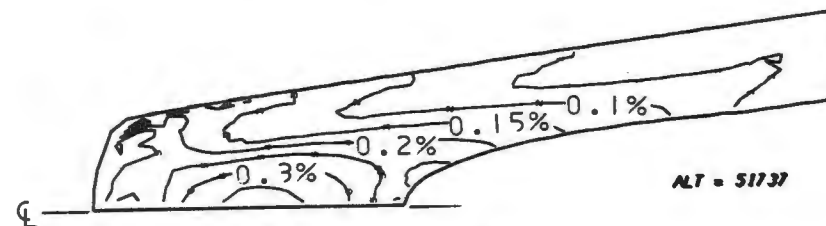
FIGURE 32
 GRAPHICAL OUTPUT FOR PIPING TEE ANALYSIS



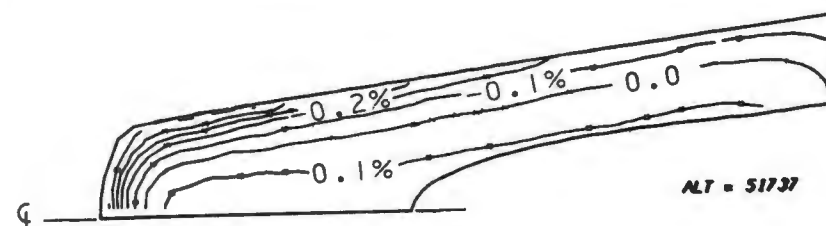
ERODED SHAPE AND ISOTHERMS



NOSETIP CONFIGURATION



CONTOUR MAP OF
MAXIMUM STRAIN



CONTOUR MAP OF
CIRCUMFERENTIAL
STRAIN

FIGURE 33
REENTRY VEHICLE NOSETIP
ERODED SHAPE AND CONTOUR MAPS

SECTION IV

PRODUCTION GRAPHICS

To demonstrate the utility of graphical tools and to emphasize the extent to which such schemes are used, a short discussion of some major analytical tasks that have recently been completed is offered here.

Figure 32 shows a three dimensional analysis of a pipe tee that was performed using the "DAISY" code. The model consisted of 886 nodes, 872 quadrilateral bending elements, 4242 unknowns, and was analyzed for five mechanical loading conditions including internal pressure. Contours of surface stresses, deflected plots, and graphs of stresses along preselected lines of the structure were used extensively. The entire reporting task required less than a week and consisted primarily of assembling graphical computer printout onto larger report format sheets.

A further value to be obtained from graphical output is shown in Figure 33, an output from a re-entry vehicle analysis. This figure shows the automatic model geometric changes as the model ablates and demonstrates the variation in the structure with altitude that is used as thermal load input. The structural model is overlaid directly onto a thermal model which has been run previously to determine thermal loads at various altitudes. The entire analysis from the time the thermal loads are obtained is accomplished in 24 hours, including stress, strain, temperature and geometric histories. All graphics are automatically prepared and output directly in a report format.

Another example of the use of computer graphics as a data reduction tool for complex structural analysis is shown in Figure 34. The problem, an advanced elastic-plastic incremental analysis of an aircraft disc brake component, required the calculation and display of stresses and strains at any point during multiple thermal cycling. The collage summarizes the computer graphics used in the presentation of output as an illustration of the ease of visual assimilation of results. This problem was quite complex and the extensive use of graphical output added immensely to the engineer "feel" and understanding of the problems.

Two final examples demonstrating the ability of graphics to bring complex finite element analysis to full production fruition which can be cited are: a thru-bulkhead initiator subjected to severe plastic deformations was modeled, analyzed and visual reporting made in less than one day; a diode subjected to four thermal load cases resulting in plastic deformation was analyzed and graphically presented in two days, the model being generated and debugged using interactive graphical procedures.

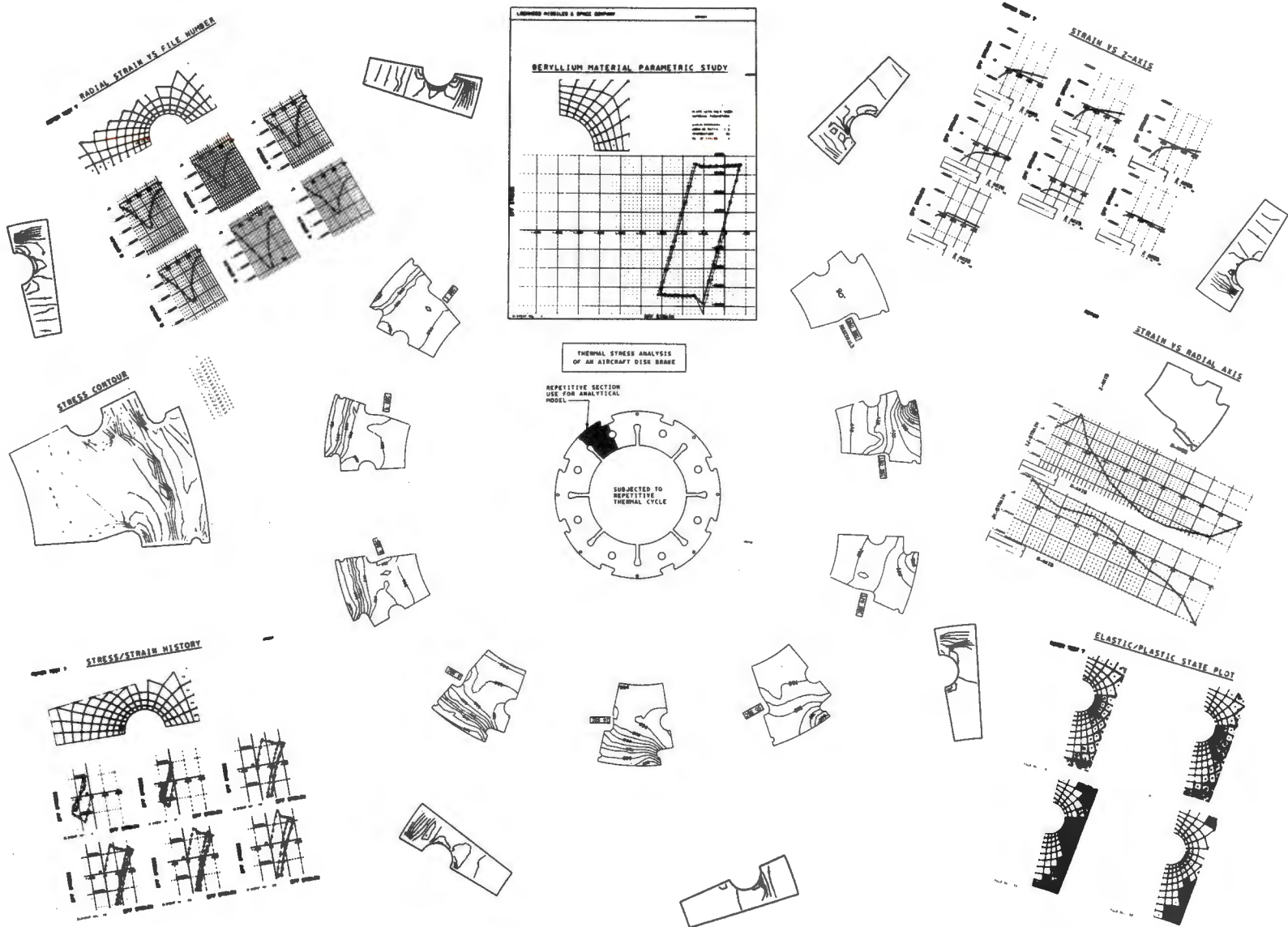


FIGURE 34.
GRAPHICAL OUTPUT FOR DISC BRAKE ANALYSIS

SECTION V SUMMARY

While a widespread effort on all aspects of finite element development is being pursued at Lockheed including; non-linear analysis of general structures, incompressible arbitrary solids, thermal fatigue and creep, dynamics, buckling, super-elements, and high-speed equation solvers, we believe that the major factor common to, and necessary for, the implementation of all such developments into a usable production mode of operation is the availability of an extensive range of graphics packages. Such packages obviate the necessity for poring over many hundreds of pages of printed output, enables rapid checking of results and input data, and, finally, allows large scale, complex analysis tasks to be successfully completed in a minimum of time and with a minimum cost. Therefore, in addition to the rapid development of an extensive library of finite element codes we are firmly committed to the concept of advanced graphics packages, for both the interactive and batch modes, to enable such programs to truly become viable tools for large scale structural analysis problems.

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