EXPERIENCE IN THE APPLICATION OF A FINITE ELEMENT SYSTEM TO THE ANALYSIS OF COMPLEX PRESTRESSED CONCRETE PRESSURE VESSELS

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SUMMARY

The increasing geometric complexity of PCPVs requires an accurate mathematical idealization of the shape of the structure. Finite elements of the isoparametric type provide one answer to this problem. The commercial availability of finite element analysis packages requires the designer to make a careful selection of a suitable package and adapt and extend that system to suit his particular needs. This paper discusses the application by Taywood Engineering Ltd., of the Atkins Stress Analysis System (ASAS) to the analysis of complex, multi-podded PCPVs.

Having chosen the smallest representative segment of the vessel, it was necessary to decide on the fineness of the element grid to be employed. Two criteria impinged on this decision, computing cost and maximum practical run-time. Best utilization within these cost/time limits was achieved by employing efficient solution methods and by utilizing restarts to split the job into more manageable segments. The job size was then determined by the decomposition of the stiffness matrix which was the largest discrete segment of the analysis.

Preparation and verification of data, for structures of the size considered, presented an arduous task. Around 5000 nodes had to be defined in terms of Cartesian co-ordinates and their positions relative to each other. Methods were developed to automatically generate regular portions of the grid, but irregular areas had to be inserted by hand. Verification was assisted by a number of plotting programs employing drum and V.D.U. plotters together with logical checks on the geometry and loading data.

The analysis of PCPVs must take account of the time dependent nature of material properties. Previous work has shown that the use of specific strain curves based on laboratory test results and McHenry's time dependent superposition law for changing loads yield a good approximation to the long term behaviour of concrete. A suitable temperature dependent equivalent 'E' value was automatically chosen for each element by use of the spatial temperature distribution provided by the ASASHEAT program.

The designer's task in interpreting the results arising from the analysis was aided by writing programs for the manipulation, testing and presentation of the output. Combined stress components at every node were obtained from the various elements of each load case. Principal stresses and directions were calculated. These results were then tested against the requirements of the British Code B.S.4975; although any suitable set of rules could be used. Values requiring more detailed consideration by hand methods were indicated in the output. Finally, the results were presented in the form of principal stress contour plots.

The significance of this work lies in the fact that a suite of programs has been built around a general finite element system to satisfy the precise needs of a vessel designer. A design office tool has been produced which is economic in terms of the time and effort required in data preparation and assessment of results.

1. Introduction

The design of commercial PCPV's demands the provision of a structure which can safely withstand the high pressures and temperatures associated with a nuclear reaction whilst being economically priced. Since safety of operation is of the utmost importance the cost of the structure can only be limited by obtaining an accurate understanding of its behaviour and, hence, minimising its size. The key to this close understanding of structural behaviour, and economic design, lies in the use of suitable analysis techniques. It may be seen that vessels of the complexity now envisaged require the use of powerful analysis methods.

For the Hartlepool style of pressure vessel with its regular geometry and simple interconnecting ducts, the dynamic relaxation technique has yielded satisfactory results. However, in undertaking the design of multi-podded PCPV's for the British H.T.R. and the German H.H.T., involving a complex of variable size vertical and horizontal penetrations, Taylor Woodrow recognised that this method of analysis could not sensibly provide solutions of the necessary accuracy. In this approach, a regular grid in polar or cartesian co-ordinates is placed over the whole structure and voids can only be represented by the modification of "E" values to provide an approximation to the correct stiffness. This means that values of stress at internal boundaries can be grossly distorted. A major problem also exists in the evaluation of suitable "E" value modification factors in 3-dimensional structures.

Finite elements of the isoparametric type shown in figure 1 permit the modelling of curved surfaces and can be used to give an accurate representation of the shape of the structure and provide values of stress and deflection throughout. The availability of commercial finite element packages meant that it was unnecessary for a totally new system to be evolved and a careful survey of the market was conducted. Several criteria were laid down. These included availability of isoparametric elements, heat flow analysis facilities, large computing capacity and good technical support. This latter requirement was of the greatest importance because it was known that modifications and additions to the basic system would be necessary to meet the specific needs of the vessel designer. The Atkins Stress Analysis System (ASAS), offered by Atkins Research and Development on the CDC 6600 of SIA Ltd. was selected as providing the best basis for the proposed work.

2. The Finite Element Model

The first task in modelling a vessel in finite element terms is to decide on the smallest segment of the vessel that can be used to represent the whole. Vessels with podded boilers of common size can be satisfactorily dealt with by analysing a segment only a half boiler pitch in circumference and it may, further, be possible to split the vessel at the equator into two part-height segments. However, in the case of vessels with significant horizontal penetrations in the bottom cap, such as the German HHT vessel, planes of symmetry are dictated by these penetrations and correspondingly larger segments result.

The chosen segment has then to be divided into a grid of suitable fineness. In theory there is no limit to the number of elements that can be assembled to create the desired structure but in practice the following restrictions occur:-

(i) For any given computer there is a limit to the size of matrix that can be stored, although this is not, in itself, significant with current machine hardware.

(ii) There is a practical limit to the duration of any single computer run which is related to the average time between machine breakdowns.

(iii) In the commercial world there is a limit to the amount of money that can be spent on an analysis, both in terms of the man hours required to prepare data and assimilate results, and in terms of the cost of computer time.

The matrix size, and, more important, its shape has a strong influence on run duration. Here a major problem arises in that it is unrealistic to expect a large computer to run for long periods without breakdown or fatal error. In the case of the CDC 6600 a maximum anticipated run duration of 15 hours was thought to be realistic. In order to make best use of the available time the ASAS system splits the analysis into discrete stages. Data may be stored at the end of any stage and used as input for a restart at the next stage. Thus failure at any point means a return only to the end of the last stage. The fineness of element grid is thus conditioned, to a large extent, by the time required for the longest stage, generally the decomposition of the structural stiffness matrix. This process requires efficient solution methods and can be seen to be of great importance in providing the designer with an economic tool.

3. Data Preparation and Checking

The most laborious and time consuming part of the data preparation lies in the definition of the geometry of the structure and the chosen grid. Input to the main program is in the usual form of nodal co-ordinates and member incidences (referred to in the ASAS system as "element topology"). Hence small independent programs have been written by Taylor Woodrow to generate data, in a form acceptable to ASAS, for regular portions of the grid. It is advantageous to establish a grid which is as regular as possible throughout the structure so that a minimum amount of hand adjustment is necessary.

It is of crucial importance that the nodes of the structure are numbered in such a manner as to minimize the numerical difference between the highest and lowest node numbers within any element. This difference has a strong influence on the shape of the assembled stiffness matrix and hence on the solution time. It has been found well worth testing several numbering sequences before deciding on the final scheme. It is worth noting that discontinuities in grids and structures can lead to excessively high node number differences and should be avoided where possible even at the expense of additional nodal points. Examples of grids used on a vessel for the HHT project are shown in figures 2(a) and (b).

The vessel illustrated required the definition of around 5000 nodes in terms of co-ordinates and topology and obviously a major problem exists in the verification of such quantities of data. Checking was done in several stages. First the acceptability of the data to the main program was checked simply by a card read and list routine. Then individual "planes" of nodes were plotted on a drum plotter; a method which can only give 2-dimensional pictures. The data was next submitted to the checking stage of the ASAS system which applies logical tests on the self-consistency of information supplied and checks that the geometric condition of each element lies within limits designed to ensure reasonable results. Finally, the data was checked by the use of more sophisticated plotting techniques designed to present a 3-dimensional veiw of the structure. At first this was achieved by the use of a drum plotter program giving views of the structure from a number of predetermined orientations; plan, elevation, oblique and so on. However, this equipment has now been superseded by a suite of programs linked to a Tectronix storage tube which permits the rapid re-drawing of chosen parts of the grid from any angle and at any scale. The best check on the validity of data is obtained by continuous observation of the structure as it is built up on the screen, supplemented by hard copies of any interesting views.

4. Selection of Material Properties

The deflections, and, to a lesser extent, stresses within a pressure vessel are closely dependent on the material properties of the structure; elastic modulus, creep and shrinkage. Much work has been reported on this topic and various approximations to the time dependent nature of these properties proposed. The use of specific strain curves, based on laboratory test results(1) and McHenry's time dependent superposition law for changing loads(2) have been shown to give good agreement with actual situations. Thus it was decided to adopt this approach in the selection of material properties for the finite element analysis. A problem follows immediately from this decision in that the effective "E" values of the structure are changing in magnitude and relative to each other, from element to element, throughout the life of the structure. Thus, at any two points in time different finite element "structures" exist, each with a different stiffness matrix, each requiring separate solution. Furthermore, at any one time different effective "structures" exist for different types of loading, due to creep behaviour. For example, at early life, under proof pressure test conditions, prestress may have been on for, say, 2 years resulting in a high specific strain whilst pressure will have been applied almost instantaneously, giving a low specific strain.

It is, therefore, necessary to analyse a limited number of "structures" which will reasonably represent the different conditions which can exist throughout the life of the vessel. Further cases can be generated by factoring the results of the basic cases. Three conditions have been selected; cold vessel under prestress only, hot vessel at early life and hot vessel at late life, with three corresponding sets of "E" values. For the cold vessel a single value of "E" related to the ambient vessel temperature was chosen by hand and modified in the standpipe region to take account of the different stiffness of this composite area(3). For the hot vessel it was necessary to relate the "E" values to the individual element temperatures. Here, a post-processor to the ASASHEAT program was written, which takes the calculated nodal temperatures for each element in turn, finds an average element temperature and then selects a suitable "E" value from a hand produced tabulation of "E" against temperature for the particular set of loading conditions.

5. The Applied Loads

Loading on the structure is of three types; pressure, prestress and temperature. The ASAS system copes readily with uniform or trapezoidal pressure loads on element faces and point loads on nodes. Internal pressurisation is simply dealt with in that each element face subjected to a particular magnitude of pressure is listed and assigned that pressure. The problem arises in actually ensuring that all such faces are found and no extra ones added. The checking routines within ASAS establish the validity of element face data but cannot indicate whether these are the faces that the designer is intending to be loaded. The authors' companies are both working on aids to the designer in the identification and plotting of free faces within complex structures.

Prestress loading in the type of vessel dealt with consists of circumferential prestressing of the wire wound type based on the Taylor Woodrow wire-winding system(4), together with linear tendons in the vertical direction and, in the case of the HHT vessels, in the radial direction at the level of the turbine tunnels. Wire-wound prestress can be adequately represented by the application of pressure loads to the outside element faces. Anchorage loads on the top and bottom faces of the vessel are best represented by equivalent point loads at the surface nodes.

Temperature loading was applied directly from the ASASHEAT run as a series of nodal temperatures, a linking program being available to generate the required ASAS data automatically.

6. Computer Processing

The sheer size of analyses of this nature places severe demands on computer hardware and software. On the technical side, some problems were encountered which necessitated alteration to the ASAS package. These changes were concentrated on the assembly and decomposition stages; the algorithm of the former being re-arranged to produce the stiffness matrix in row order rather than the original column order. This led to significant reductions of overall time for problems with very high bandwidth (or node number difference on any one element). The mode of reading and writing the stiffness matrix was changed from sequential to direct access, enabling a considerable reduction in the number of disc accesses and a corresponding reduction in elapsed time. The only other changes to the software were required to avoid some existing inconsistencies in the machine operating system.

As usual on such projects, the required changes mentioned above came to light and were incorporated during the first analysis. Subsequent runs have been processed as production jobs, for which we have adopted the following operation sequence.

Each analysis is processed complete in a single session, which entails booking the machine for periods of up to 22 hours at a weekend. Although ASAS provides a comprehensive restart facility this is utilised only as an insurance against machine malfunction, and to break up the run for convenience during the session. The major points leading to this decision are as follows:-

(i) A typical requirement is for 35 million words of disc storage. This would not normally be available and clean disc packs have to be mounted. It takes the operators approximately an hour at the start and finish of each session to prepare the machine. This two hour overhead reduces the effective time available for overnight runs during the week.

(ii) In order to save intermediate results on magnetic tape for a subsequent restart at a different time, up to twelve 2400 ft. tapes would be required. The time taken to write and read these tapes further reduces the effective overnight time.

(iii) The major portion of the elapsed time is spent in the decomposition stage during which restarts are not yet available. This longest stage amounted to 15½ hours for the largest analysis so far undertaken. The presence of restarts would not be a significant factor, as the above two points are dominant, except for additional insurance against machine failure.

(iv) The constraints on overnight bookings are very tight in order that standard daytime bureau service is maintained. This can cause loss of a run if insufficient time is available to recover following machine malfunction. Weekend bookings are more flexible.

Both the machine operators and the systems staff responsible for running ASAS have amassed considerable expertise in handling these large analyses. The most recent set of three analyses were run in five consecutive weekends of which the second and third were not required, processing of results from the ASASHEAT run being necessary before the final two analyses.

7. Post-Processing of Results

As with all finite element programs a formidable mass of output data is produced from which the designer wishes to distil only the salient points. This distillation process was greatly aided by the writing of post-processing routines which were designed to produce principal stresses and directions for combined loading cases. These results were then tested against a chosen set of permissible stresses. The present program utilises the provisions of the British Pressure Vessel Code, BS 4975$^{(5)}$, but any suitable set of rules could be incorporated. Output from the post-processor consists of a nodal list of principal stresses and directions together with a stress indicator. The indicator is intended to give a coarse guide to the acceptability of the particular set of stresses such that the designer can dismiss all values which are obviously satisfactory and concentrate on those which require detailed attention. A flow chart for the testing of stresses against the code is shown in figure 3.

8. Presentation of Results

Having produced the results and assessed their acceptability it is desirable to be able to display them in some readily assimilated fashion. Various methods were contemplated but it was decided that the plotting of stress contours on chosen planes through the vessel would give as good a representation as any. Programs were, therefore, written to select the stresses at nodes within specified areas defined in polar co-ordinates. It was found convenient to examine vertical and horizontal sections, typical examples of which are shown in figure 4.

The selected stresses and associated co-ordinates (modified into a 2-dimensional plane) were then passed to a commercially available contour plotting program$^{(6)}$ which carries out a numerical interpolation process and outputs results in the form of annotated contour lines on a drum plotter. The addition of the boundary lines by a draughtsman leads to the sort of picture shown in figures 5(a) and (b). A similar process has been used for the presentation of isotherms arising from the ASASHEAT analysis.

9. Future Developments

Little has been said about deflection and strain results. This is because the type of design so far undertaken with this new tool has been limited to feasibility studies where axisymmetric strain results from dynamic relaxation analyses have been adequate. The relative movement of key components has been studied by a comparison of nodal deflections output by the present program, but further work must be done to automate the process as far as possible and to take account of the possible local variations in material properties and loadings which can be so important. Further work is in hand to convert the available deflection data into reliable strain information for use in liner design.

In conclusion, it can be seen that a finite element system of general application has been taken and extended by pre- and post-processing programs which have tailored the system to the precise needs of a vessel designer. Furthermore, in tackling structures of such size, the basic system has had to be stretched to cope with the handling of very large matrices requiring considerable systems skill. The result has been the production of a design office tool of great power, which, though seemingly expensive, is truly economic in terms of the return of detailed analytical knowledge for man-hours spent in data preparation, assimilation of results and presentation.

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HOCHTEMPERATUR-REAKTORBAU GmbH,
Kernforschungsanlage Jülich GmbH,
NUKEM GmbH,

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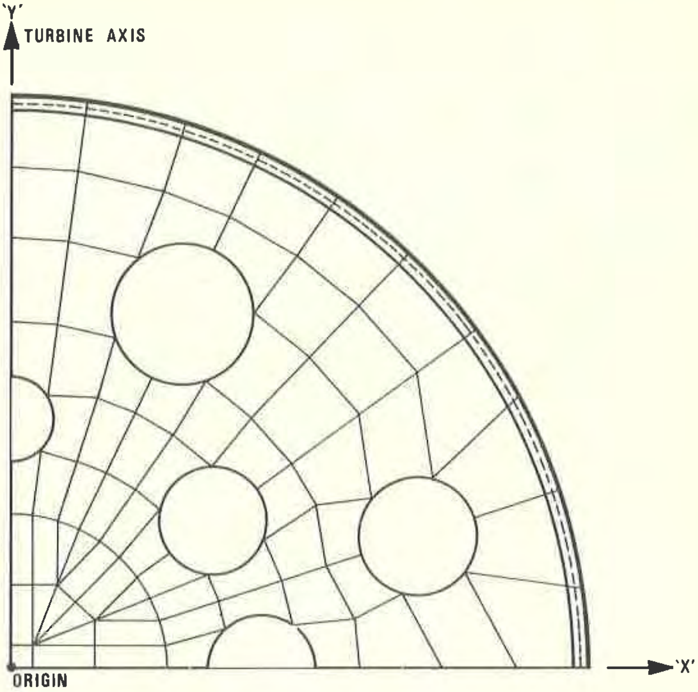


Figure 2b Typical Horizontal Grid

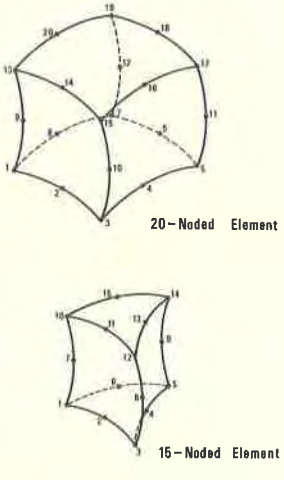


Figure 1 Finite Elements of the Isoparametric Type

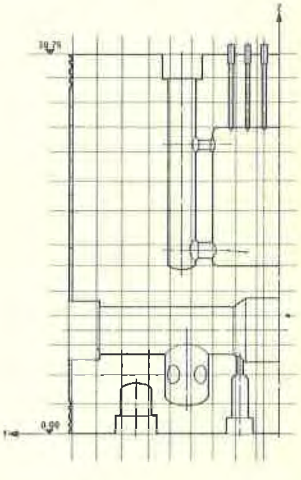
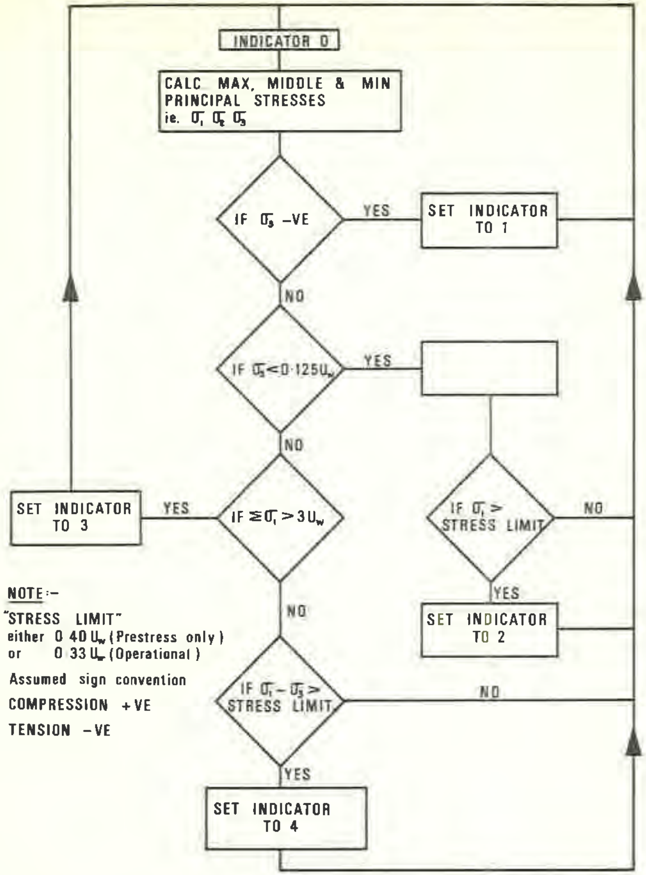


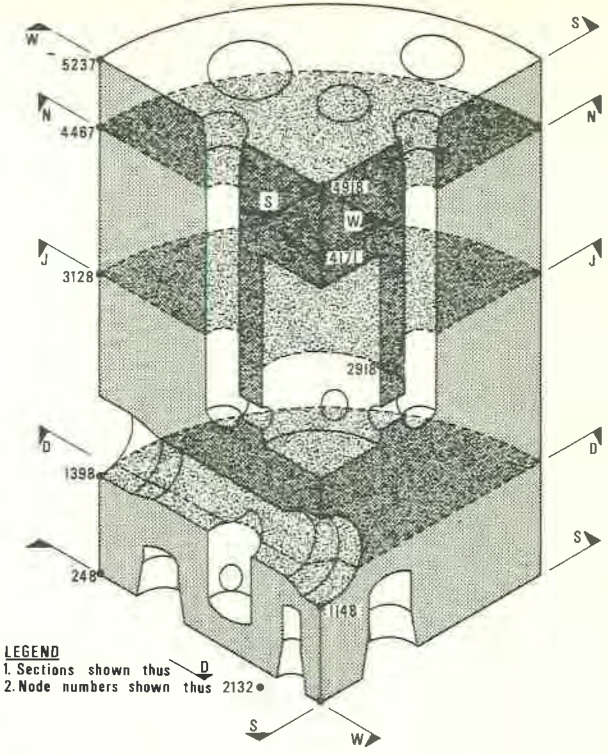
Figure 2a Typical Vertical Grid



NOTE:-
"STRESS LIMIT"
either 0 40 U_w (Prestress only)
or 0 33 U_w (Operational)

Assumed sign convention
COMPRESSION +VE
TENSION -VE

Figure 3 Flow Chart for the Assessment of Principal Stresses



LEGEND
1. Sections shown thus D
2. Node numbers shown thus 2132●

Figure 4 Typical Sections for Stress Plots

H 2/3

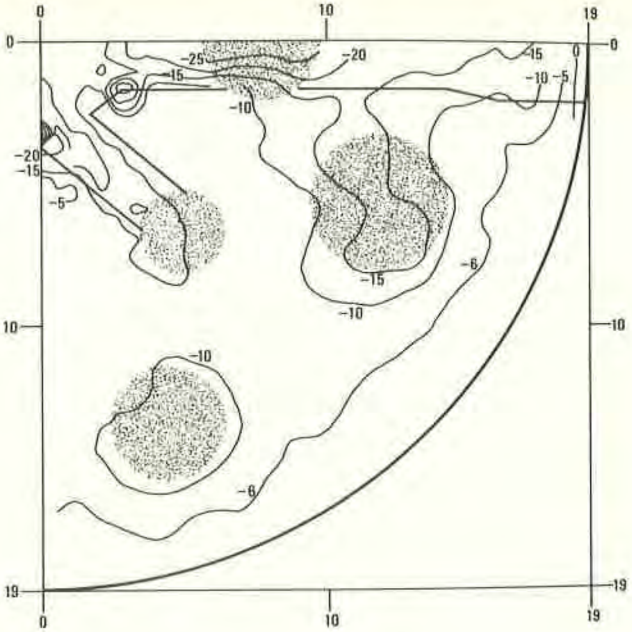


Figure 5a Stress Plot Example 1

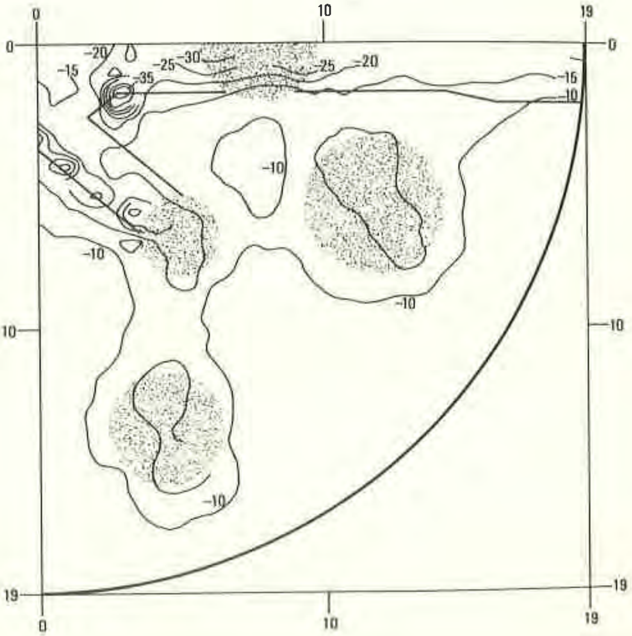


Figure 5b Stress Plot Example 2