A UNIFIED APPROACH FOR INTERIOR CONCRETE DESIGN

T. H. CHEN, G. F. DAVENPORT

Gilbert Associates, Inc., P.O. Box 1498, Reading, Pennsylvania 19603, U.S.A.

SUMMARY

A unified computer oriented approach is presented for the complete analysis and design of the reactor building interior concrete for a PWR plant. The finite element method is used with a substructure technique to prepare mathematical models of the major structural elements inside the reactor containment building. An overall model, with the only restraint boundary being the contact surface between the interior slab and the reactor building foundation, is used to study the hybrid response of the structure to complex operating and accident loading conditions, and to establish displacement boundary conditions for various detailed substructure models. In this paper, emphasis is placed on modeling techniques with respect to geometry and the characteristics of the applied loads. Interesting results are presented concerning the hybrid structural action of the PWR and the transmission of applied loads through the structure.

The lateral and vertical seismic forces may generate uplift under the mat. Results obtained in this study indicate that application of traditional rigid mat design concepts leads to unconservative moments and displacements in the vicinity of walls and supports and excessive conservatism in other areas. This is caused by local kinking of the rather flexible mat under the action of large seismic forces being transferred to the foundation. Additionally, it is seen that the interior structure responds to lateral loads as a closed section thin-walled cantilever beam with the supported end free to warp. Horizontal seismic shears are transmitted to the foundation through shear flow in the walls and *cannot* be distributed using the rigidity approach which considers only the rigidity of the wall in the direction of interest. The present approach is consistent with thin wall beam theory and yields accurate shear coefficients for use in lumped parameter seismic models.

In the past, thermal loads were considered to be self-relieving and little emphasis was placed on design for thermal loads. However, in the interior structure, the stress introduced on one structural element due to the thermal expansion of the other structural element should not be classified as self-relieving. The analysis results indicate that the thermal load is quite severe and controls the design in the lower portion of the secondary shield walls.

The mezzanine floor and the operating floor function as stiffners for the steam generator compartments under high accident pressure. The resulting inplane forces control the design of these floors.

Jet impingement is applied together with the appropriate pipe restraint forces. Due to the concentrated character of the load and the high local stresses a substructure model is made. The stress propagation path is clearly reflected in the analysis results and rebar is added to ensure the safety of the structure.

Since the model size is limited by the computer capacity and the cost, it is impossible to model in all the openings in the overall model. A substructural model is then made and the displacement boundary is adapted from the overall model. The analysis and design generate enormous quantities of data which require interpretation to provide an adequate amount of reinforcing steel. The utilization of pre-processors and post-processors is emphasized with respect to the manipulation of numerous load combinations and design of reinforcing steel.

This paper points out the importance of modeling technique and reinforces the concern for good analysis of hybrid structures such as the PWR interior concrete. By means of a detailed example the transmission of applied loads through structure is studied. It is seen that the use of some computerized structural analysis system is necessary to accurately predict hybrid structural action. From an economic and schedule point of view, a unified approach is highly desirable because it encourages careful planning and results in a logical flow of data from one step to the next.

1. Introduction

A unified computer oriented approach is presented for the complete analysis and design of the reactor building interior concrete for a PWR plant. The finite element method is used with a substructure technique to prepare mathematical models of the major structural elements inside the reactor containment building. An overall model, with the only restraint boundary being the contact surface between the interior slab and the reactor building foundation, is used to study the hybrid response of the structure to complex operating and accident loading conditions, and to establish displacement boundary conditions for various detailed substructure models.

2. Finite Element Models

2.1 Overall Model

The interior structure of the reactor building consists of the primary shield wall, secondary shield walls, fuel transfer canal, mezzanine floor, operating floor and basement slab. The primary shield wall is essentially a reinforced concrete right circular cylinder which encloses and supports the reactor vessel. Unlike the inside surface of this wall, the exterior is in the form of an irregular polygon to accomodate surrounding structural elements such as the secondary shield walls and the fuel transfer canal slab and walls. The secondary shield walls form three compartments which are of polygonal shape in plan, and form enclosures for the reactor coolant system equipment. Typical plan and section views of these structures are shown in Figures 1a and 1b, respectively. A composite finite element model consisting of beam, triangular plate and solid elements was generated for all the significant interior structures. The particular triangular plate formulation used in the present study modeled the stretching, bending and transverse shearing modes of deformation. The only boundary condition required for this overall model occurred at the contact surface between the basement floor slab and the reactor building structural foundation mat. Discrete nodal springs determined by elastic half-space theory were used to simulate the foundation material at this interface.

2.2 Detailed Model

Detailed features such as major openings and high-intensity concentrated forces from equipment supports, pipe restraints and fluid jets occur at various locations within the structure. Since model size is limited by computer capacity and cost, it is impractical to use a refined mesh to represent such details in the overall model. To properly predict stretching and bending behavior in areas where high stress gradients are expected, a substructuring technique which utilizes displacement boundary conditions is used. Several suggestions concerning detailed models are listed below. (a) The design information from one detailed model could apply to different locations in the interior structure. For example, some pipe restraints in different loops are similar to each other and based on engineering judgment the most severe one may be chosen to perform the analysis and design. (b) Try to eliminate the unnecessary loading combinations. A detailed model is made for a special area in the interior structure and most of the time it is governed by special loadings which may be determined from the overall model. (c) The boundaries of the detailed model should be established away from the area of interest and may be determined from studying deflection curves of the overall model. An example depicting this concept is presented in figures 4A, 4B and 4C.

3. Loadings

3.1 Seismic

Seismic loads are applied as equivalent static loads obtained from a time history seismic analysis of a lumped-mass model. The equivalent static nodal forces applied to the finite element model are computed from the maximum accelerations at each lumped mass. The shears and moments due to the equivalent static loads are generally greater than these computed in the seismic analysis. This is caused by the phasing difference between the lumped masses which cannot be considered in the equivalent static analysis. It is possible to use correction factors based on a comparison of the shears and moments from the seismic analysis and the equivalent static analysis. Since the difference is usually small, the correction factors may not be required. The three components of seismic loading are applied to the finite element model independently. After the static analysis the SRSS method is used to determine the stress resultants in each element. Some plots have been made to aid in the study of the load transmission due to the individual seismic inputs. Figure 5 presents the internal axial forces in the wall due to horizontal input. Since there is no external vertical force applied in this figure, all the axial forces are introduced by the moment at that elevation. It is clearly reflected in this figure that the moment distribution is different from the simple beam analogy. Figure 6 shows the shear flow in the walls. This plot agrees with the thin wall beam theory and is different from the rigidity approch which considers only the rigidity of the walls in the direction of interest. Figure 7 presents the uplift in the basement slab. The SRSS method is not applied due to the nonlinear characteristics of this problem for which the principle of super-position does not hold. The uplift due to the seismic loads could not be determined without the presence of gravity loads. In this study the dead load is applied together with the vertical and horizontal seismic input.

3.2 Thermal

In thermal analysis both the normal operating and accident conditions should be taken into account. The normal operating conditions include start-up, shut-down and steady state. The accident condition is generated from postulated pipe breaks and blowdown analyses. Time dependent variations of thermal transients through the thickness of the concrete should be considered in evaluating thermal stresses for both normal operating and accident conditions. The temperature distribution through the thickness of a section under transient conditions is usually non-linear. In general, a linear temperature gradient[1] through the thickness of a plate is the highest order admissible distribution which is compatible with the assumed kinematic degrees of freedom associated with thin plate theory. It is therefore necessary to determine equivalent mean and linear components of the actual non-linear gradient. Mean temperature is generally associated with the interior concrete walls and floors since they are heated uniformly from both sides. The basement slab is heated from only one side and is therefore subjected to both uniform and linear temperature components. In either case the appropriate thermal loading is applied to a linear elastic finite element model. A typical thermal analysis displacement curve is presented in figure 8.

3.3 Accident Pressure

The accident pressure is generated by the postulated pipe breaks. The equivalent static load, which includes an appropriate dynamic load factor to account for the dynamic nature of the load, is applied to the structure. When the pipe break is postulated in one compartment the associated pressure is then applied to that particular compartment only. In this case all surrounding structures function as stiffners for that compartment. One example is shown in figure 9. This pressure is not only important for designing that particular compartment but also for evaluating the surrounding structures. For example the resulting inplane forces in the mezzanine floor and the operating floor control the design of these floors.

4. Post-processing and Design

4.1 Computer Application

The system stiffness matrix is generated from the element stiffness matrix and then decomposed into triangular form.[2][3] By means of forward and backward substitution of each load vector the final nodal displacement vectors are obtained. The stress resultants in each element are computed from the nodal displacements. At this stage a post-processor may be used to rearrange the results of the analysis into convenient forms to aid design.[4] In each step of the analysis a lot of data is generated and saved, the most important of which is the decomposed stiffness matrix, displacements at each node and stress resultants in each element. The decomposed matrix is needed for subsequent analysis of additional loads. The stress resultants for the basic loads are used for loading combinations. This data may be placed on secondary storage such as a tape or disk. Cost is a major factor for storage selection. For example, a 1900 node finite element model generates a decomposed matrix which requires 24000 storage data blocks at a cost of about 300 dollars per day for on line storage. On the other hand all the information could be stored on one 9 track tape at a cost of only 20 cents per day. This example is based on CDC equipment and current price schedules.

4.2 Loading Combinations

The required loading combinations are listed in Document (A), Structural Design Criteria For Category I Structures Other Than Containment and the U.S.N.R.C. Standard Review Plan. The SRSS method for the combination of effects of earthquake components has been generally accepted by these guides. However, after the SRSS application the signs of all of the stress resultants are lost. As a consequence a lot of combinations may be generated by simply varying the sign. As an example, in reinforced concrete design the force P and moment M are of interest to the designer. The interaction between P and M must be considered in the rebar design. There are four combinations generated by varying the sign and if a designer has to examine each of the four possible cases, the loading combinations due to other loadings must be quadrupled. The designer is faced with the task of digesting tremendous amounts of data in order to provide an adequate amount of reinforcing steel.

4.3 Reinforced Concrete Design

The reinforced concrete members are designed in accordance with the ACI 318 code[5] and the ACI 349 code. The design procedure is usually a straight-forward task. In design of the interior structures this task becomes difficult due to the enormous number of load combinations. A computer code is developed to perform the design and calculate the rebar requirement at each element. The final production is presented in two different forms. First the rebar requirements are listed under each element, for each loading and each stress resultant component. This is a complete listing but not very convenient in presentation. A second listing is produced based on the total rebar requirement in an element. The top most cases are also tabulated in a very condensed form.

5. Summary and Conclusion

The interior concrete structure constitutes a major and significant portion of the reactor building, its primary function being to resist the effects of practically all the postulated accident conditions inside containment. Due to the complexity of the geometry and loading, a unified computer oriented approach is presented for the complete analysis and design of the structure. The finite element method is used with a substructure technique to study the hydrid response of the structure to complex operating and accident loads, and to establish displacement boundary conditions for various detailed substructure models.

The basic loads which have the most affect on overall structural response include seismic, operating and accident temperatures, and sub-compartment accident pressures. Horizontal and vertical seismic input may generate uplift under the mat, and results obtained in this study indicate that application of traditional rigid mat design concepts leads to unconservative responses in the vicinity of walls and supports, and excessive conservatism in other areas. Horizontal seismic shears are transmitted to the foundation through shear flow in the walls and cannot be distributed using the rigidity approach which considers only the rigidity of the walls in the direction of interest.

Highly restrained structural elements are susceptible to serve initial loading due to differential thermal movements resulting from operating and accident temperature transients. This may lead to unacceptable cracking during normal operation with a reduction in ultimate strength under the subsequent action of accident loads. Internal forces and moments estimated solely on the basis of an uncracked elastic analysis may tend to overestimate the severity of the problem since some types of thermal loads relax as structural stiffness is reduced by cracking.

Sub-compartment accident pressures are resisted by complex structural action involving several elements of the structure at once. This type of hybrid response is best predicted by an overall finite element model of the structure. The mezzanine and operating floors function as stiffners for the steam generator compartments and the resulting inplane forces control the design of these floors.

It is indicated that post-processing capabilities are very cost effective in saving time and man-power normally used to interpret raw data and accomplish the design.

Acknowledgements

The authors wish to thank Mrs. R. Chang and Mr. C. O. Keich for their dedicated effort in preparing the finite element models and drawings.

References:

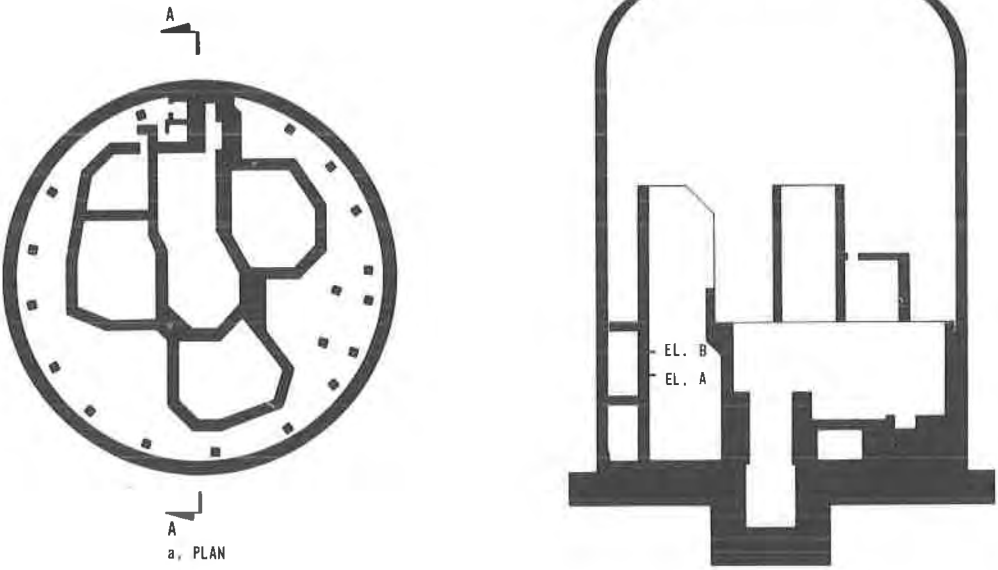
[1] Timoshenko, "Theory of Elasticity Second Edition", McGraw-Hill, Inc., 1951.

[2] Zienkiewcz, O.C., "The Finite Element Method in Engineering Science", McGraw-Hill, 1971.

[3] Cook, R.D., "Concepts and Application of Finite Element Analysis", John Wiley and Sons, Inc., 1973.

[4] Ho, P.K. and M. Stoykivich, "Analysis and Design of Nuclear Power Plant Structures", Proceedings Vol. II, Specialty Conference on Structural Design of Nuclear Plant Facilities, Chicago, Illinois, Dec. 1973.

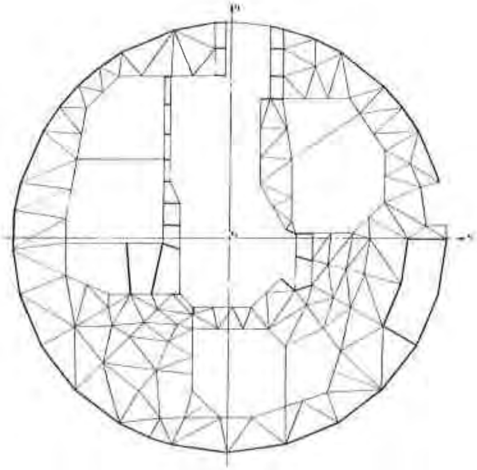
[5] ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-710". Am. Concrete Inst., Detriot, 1971.



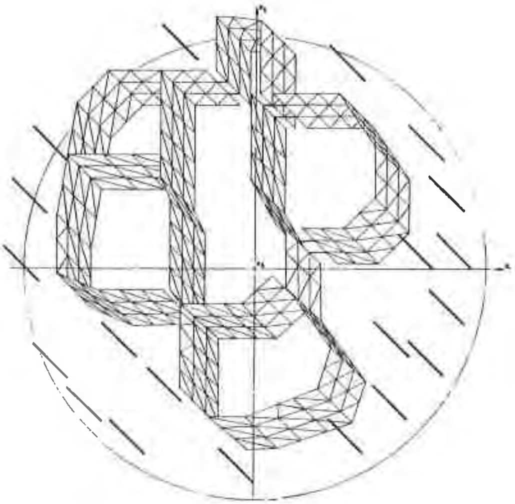
a. PLAN

b. SECTION A-A

1. INTERIOR STRUCTURES IN A PWR PLANT
   a. PLAN
   b. SECTION



2. FINITE ELEMENT MODEL - FLOOR.



3. FINITE ELEMENT MODEL - WALL.

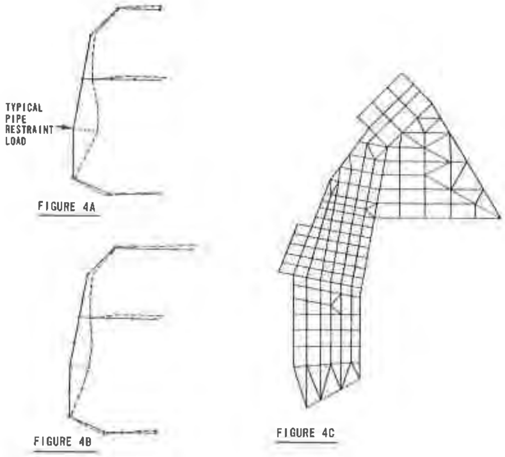


FIGURE 4A

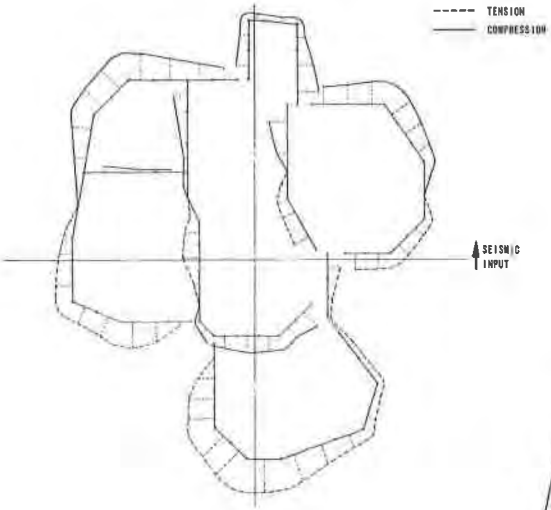
FIGURE 4B

FIGURE 4C

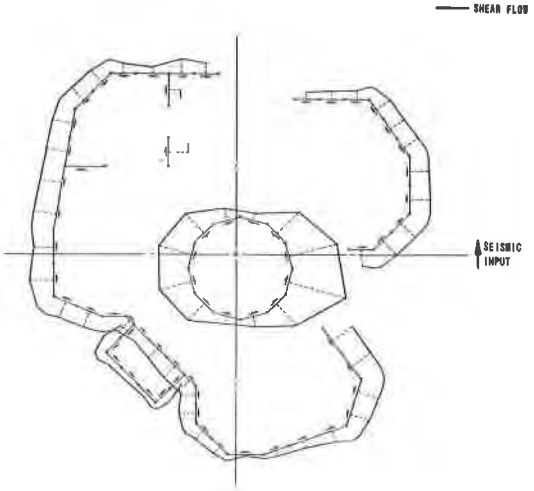
4. 4A. DEFLECTION AT ELEV. A

4B. DEFLECTION AT ELEV. B

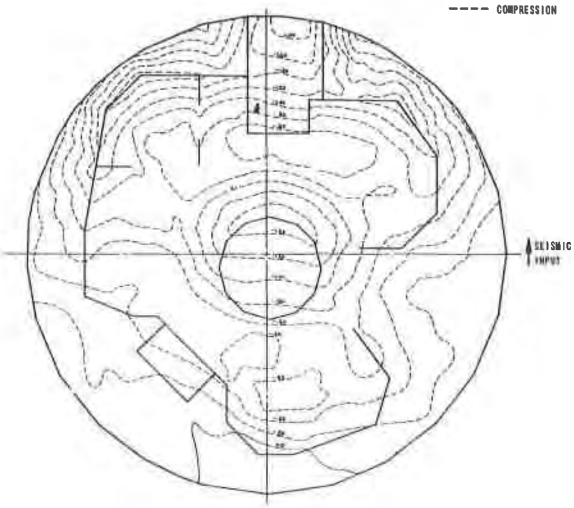
4C. FLOOR DETAILED MODEL



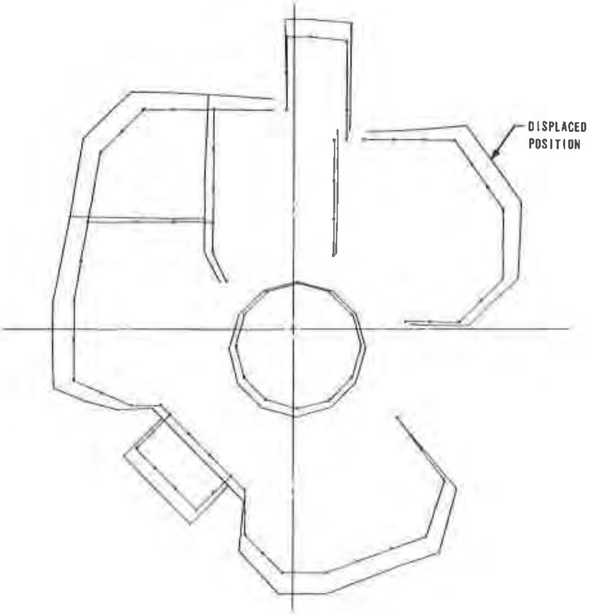
5. AXIAL FORCES DUE TO HORIZONTAL SEISMIC LOAD.



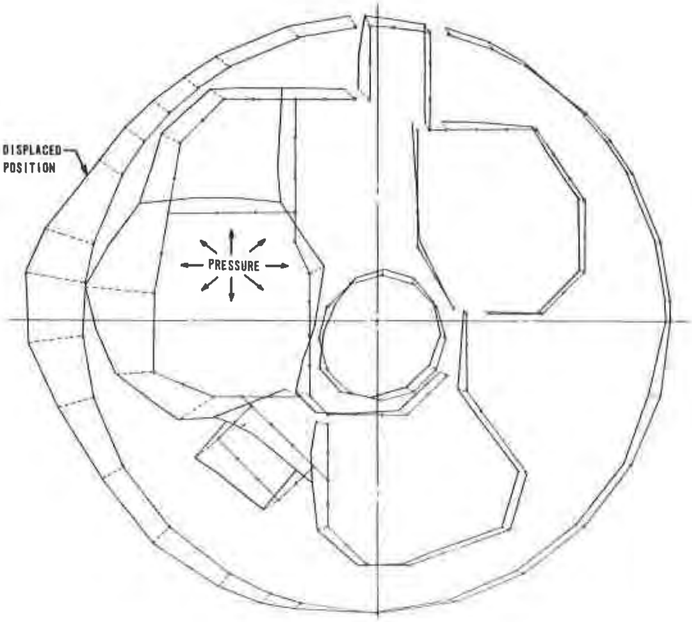
6. SHEAR FORCES DUE TO HORIZONTAL SEISMIC LOAD.



7. DISPLACEMENT AT FOUNDATION DUE TO SEISMIC LOAD AND DEAD LOAD.



8. THERMAL EXPANSION.



9. DEFLECTION DUE TO INTERIOR PRESSURE APPLIED IN ONE COMPARTMENT.