MANAGING STRUCTURAL DESIGN THROUGH INTEGRATED MODELS

AND OBTAINING INCREASED SAFETY AND ECONOMY

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ABSTRACT

The use of large finite element (FE) models for the design of reinforced concrete elements in nuclear power plants will be treated. For this technique a set of computer programs is necessary, since the amount of data is very large. With this design method a series of advantages is obtained such as: reduction of reinforcing steel expenditure, increase of safety through a better representation of the structures, an adequate control of the calculation due to the transparent method of design, reduction of design time due to the automatic computation and so on.

INTRODUCTION

The design of reinforced concrete structures in Nuclear Power Plants is a formidable task for the structural engineering due to the complexity of the structural elements, to the large amount of loadings to which the reinforced concrete members are subjected and to the high values of the acting forces.

The loadings can be of different types and additionally can be applied in various ways, concerning places, directions, intensities, time instants, etc.

The structures of a nuclear building, especially those of the Reactor Building, are rather complicated, since they are formed according to requirements of the mechanical design. The structural elements are interconnected and the whole structure works as a monolithic structure.

The design of the structural members must be performed under different design rules, which depend on the combination rules. On the other hand, the combinations of loadings need for their definition a set of factors, which are different for each combination type.

To manage all these problems it was decided, in the design of the Angra Nuclear Power Plants, Units 2 and 3, to tackle the problem of designing the reinforced concretes in a new way. The proposition was to use large finite element models, which would represent a large part of the structures, to use as much as possible computer calculations for control of combinations and to perform the determination of the reinforcement in an automatic way.

The representation of the structures can be made using the FE modeling technique. However the models can not be made as large as desirable, since there are limitations with respect to size, processing costs and so on.

On the other hand the amount of loadings and combinations can be very large, especially in the case of the internal structures of the Reactor Building, so that the numerical handling of the various load cases must be performed with postprocessed computation.

For the determination of the reinforcement, again, the manual handling would be impossible, since the number of elements, the prescribed different design rules and safety factors for the various combinations are rather numerous.

Therefore the use of the large finite element models in the design can only be introduced if a series of computer programs is available to handle all the analysis data, which are created by the structural analysis programs.

The technique treated herein was used in the design of the Brazilian Nuclear Power Plants, which are being built at the Atlantic Coast at mid course between the harbors of Rio de Janeiro and Santos. The Angra NPP, Units 2 and 3 are being designed by the Brazilian state company NUCLEN and are based on the KWU architecture. They have each the electric power of 1300 MW and the reactors are of PWR type. The responsable for the structural design of the main buildings is Promon Engenharia S.A.

This paper will treat only the design of the Reactor Building.

DEFINITION OF THE MODELS FOR THE REACTOR BUILDING

The Reactor Building is represented by five large models:

a - the Foundation

b – the Base Plate
c – the External Concrete Shell
d – the Spherical Cap
e – the Internal Structures

In Figure 1, a section across the Reactor Building is depicted, indicating the structural parts, which are related to each model. It should be noted that the foundation slab and the base plate are separated by the waterproofing membrane, so that, two different models have been used for these two groups of structures.

From these five models only the last three are represented in the Figures 2, 3 and 4.

The model of the external shell (Figure 2) represents besides the shell itself, all the structures which are connected to the shell, such as, the UJE part (Main Steam and Feedwater Valve Compartments) and the internal walls and slabs of the UJB part (Annulus or the Reactor Building). For this model it is considered that the shell and the walls rest on an indeformable support at the base plate.

The spherical cap model is more complex since there are three spherical caps, one over the other, to be represented:

a – the upper concrete cap, with a thickness of around 1,5m.
b – the steel cap, corresponding to the internal containment shell, presenting a plate thickness of 25mm.
c – the lower concrete cap, with also a thickness of around 1,5m.

This spherical cap model represents, besides the spherical caps themselves, the following structures: the ring wall, the slabs and walls connected to the spherical caps and part of the missile protection cylinder of UJA part (Internal Part of the Reactor Building).

The model for the internal structures is shown in Figure 4. All the main structural elements are modeled, with exception of the structures located outside the missile protection cylinder. The load effects of these missing elements were taken into account through applied loads, corresponding to the forces applied by them on the missile protection cylinder.

The model of the internal structures is relatively smaller than the other models. The reason is due to the large amount of loads which have to be applied on the model.

The numbers of degrees of freedom (DOF), nodes, beam elements and plate elements are shown in the Table 1, for each model.

Model	DOF	Nodes	Beams	Plates
External Shell	9237	1830	328	2467
Spherical Cap	8372	1862	921	2832
Internal Struc.	5432	1178	395	1932

Table 1. Numbers of degrees of freedom, nodes, beam elements and plate elements.

All the models represent only half of the structure. It should be noted, that the structures are not entirely symmetric, i.e., the models reproduce the actual structure in an approximate way.

On the other hand, due to the antisymmetrical loadings, actually there exist two different sets of boundary conditions for each model. For this reason each model must be analysed in two different runs, each one with the boundary conditions corresponding to the pertaining load cases.

The models for the foundation and the base plate will not be treated herein.

DEFINITION OF PROCESSED LOADINGS, BASIC LOADINGS AND COMBINATIONS

The acting loadings applied on a Reactor Building can be of different types:

a – dead loads of the structures, equipments, water, and mechanical devices,
b – loads due to the deferred deformations of the concrete such as creep and shrinkage,
c – operation loads, including equipment loads, pressure differentials, temperature, live loads, crane loads, etc.,
d – environmental loads, such as wind, temperature, buoyancy, earth pressure,
e – earthquake loadings due to OBE and SSE,
f – loads related to the postulated internal accidents, e.g., equipment reactions, piping reactions, jet pressure, jet impingement, pressure differentials, temperature, fall of devices, etc.

These different types of loads in a few cases, specially for earthquakes and postulated accidents, can be applied in various conditions concerning places, directions, intensities, time instants, and so on.

The addition of the internal forces should also be performed from results coming from models with different boundary conditions.

Due to all these reasons it was decided that a postprocessor would be necessary to handle all the analysis results. For doing that, the concepts of processed loading, basic loading and combination must be defined. The processed loading corresponds to the loading processed by the analysis program and from which results in terms of internal forces, displacements, reactions are available. The basic loading is a physically identified loading, usually caused by a single action such as, dead load, wind, earthquake from west, wind from north, postulated pipe rupture at cold leg in compartment no. 999, and so on. The combination is defined as the factored basic loadings, as prescribed by the design standards. These three definitions are represented by the expressions:

$$\{B\} = [BP]\ \{P\} \qquad (1)$$

$$\{C\} = [CB]\ \{B\} \qquad (2)$$

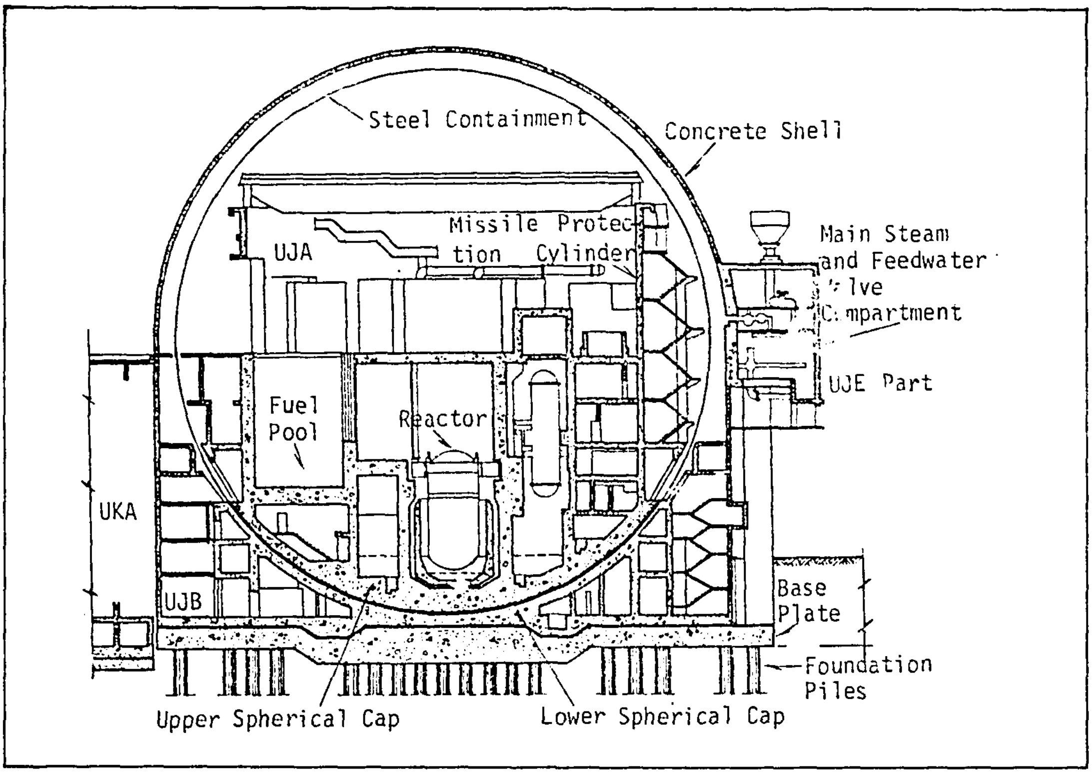

Fig. 1. General arrangement of the Reactor Building.

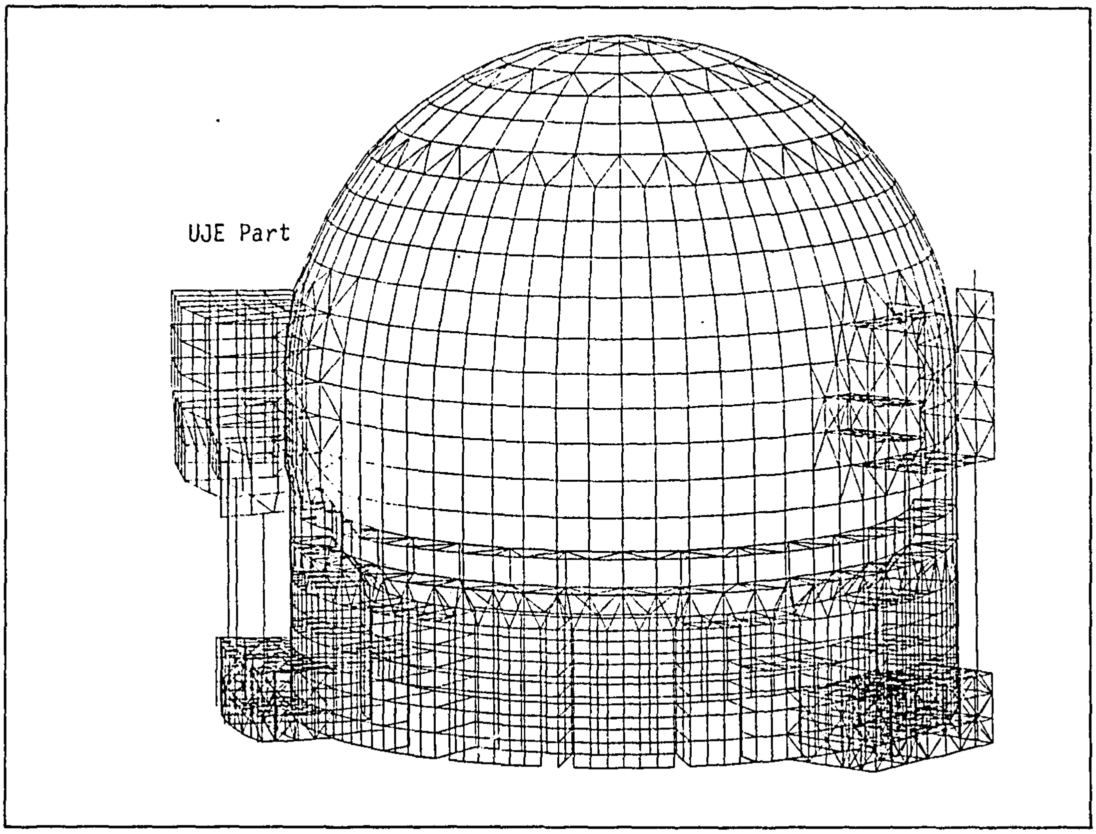

Fig. 2. Model for the external shell and the UJE Part

$$\{C\} = [CB]\,[BP]\,\{P\} \qquad (3)$$

in which: $\{P\}$ is a vector representing the internal forces for the processed loading, $\{B\}$ is a vector of the internal forces concerning the basic combination, $\{C\}$ are the internal forces of the combinations, [BP], [CB] are combination matrices defined by the user and by the standards respectively.

The calculation of the factored internal forces is performed in steps as will be shown later and only for a certain part of the structure, which is being detailed for the construction.

The requirements in terms of number of combinations are not so stringent for the models of the foundation, base plate, external shell and spherical cap. On the other hand, for the internal structures, the amount of combinations, to be considered, can be enormous, if all the possibilities should be taken into account. Some engineering judgement must be done in order to evaluate which are the important combinations. Even with that reduction the number of combinations necessary for an adequate design is very large, coming to around 180 different combinations for certain parts of the UJA. In the Table 2. the maximum numbers of loadings and combinations depending on the model are given.

Model	Processed Loadings	Basic Loadings	Combi-nations
External Shell	22	28	20
Spherical Cap	14	24	21
Internal Struct.	195	289	182

Table 2. Numbers of processed loadings, basic loadings and combinations.

It should be emphasized that the number of combinations depends on the part of the structure, which is being designed, even for the same model. The full combination for the whole model is never performed, because the required factored forces are needed in design steps, according to the construction requirements. Also to note is that the whole analysis can be performed in a single step or different steps depending on the knowledge of the prescribed loadings. Anyway if for a certain member in the upper part of the structure the acting forces are only available in a later stage, the combination program will take care of that without any problem.

At this stage of design a small group of engineers has prepared the input data for the analysis programs, defining the mathematical model and studying the available load reports, from which the loading input is defined. This work can be very well checked by the members of the quality assurance program. The results of the analysis programs are also analysed as well as the plotter representation of the mathematical model in the usual way. Since the combination matrices are easily checked also, the whole design work can be considered reliable. As the number of combinations is still very large, this whole procedure assures that the factored forces for the determination of the reinforcement have been thoroughly determined.

DETERMINATION OF THE REINFORCEMENT

The structural elements utilized in the analysis usually are beam elements and plate elements. The beam internal forces are defined through six components: axial force, two shear forces, torsion moment, two bending moments. The plate internal forces need, for their complete definition, following distributed forces:

$$n_x,\ n_y,\ n_{xy},\ m_x,\ m_y,\ m_{xy},\ v_x,\ v_y$$

in which, n stands for distributed forces, m for distributed moments, v for distributed shear forces, x and y for coordinate directions.

To design a reinforced concrete beam or a plate, it is necessary to take into consideration all these force components. First of all it is convenient to place the local coordinate axes of the members along the directions of the reinforcement. Nevertheless the reinforcement determination procedures must be performed for all the members of the model as well as for all the combinations. This is caused mainly by the design requirements, which prescribe different safety factors depending on the probability of occurrence of a determined combination. Therefore it would be difficult to know beforehand which combination type would be decisive for the determination of the reinforcement.

The reinforcement determination can be time consuming if all the components of the internal forces are taken into consideration from the start. Therefore it is more economical to treat the design of the beams and plates firstly in a simplified way, utilizing for the initial design, only the axial force and the bending moment acting in the investigated direction. After determination of the critical reinforcement, a refined reinforcement determination can be then performed, based on all the components of the internal forces and taking into consideration, of course, the interaction between force components.

At this stage of design it is necessary to design the beams and plates using reinforcement at both sides of the structural elements. However the ratio between the upper and bottom reinforcement can only be determined through optimized design, since, for most of the cases, the solution of the problem of determining the amount of reinforcement of a beam or plate with top and bottom reinforcement is indetermined,

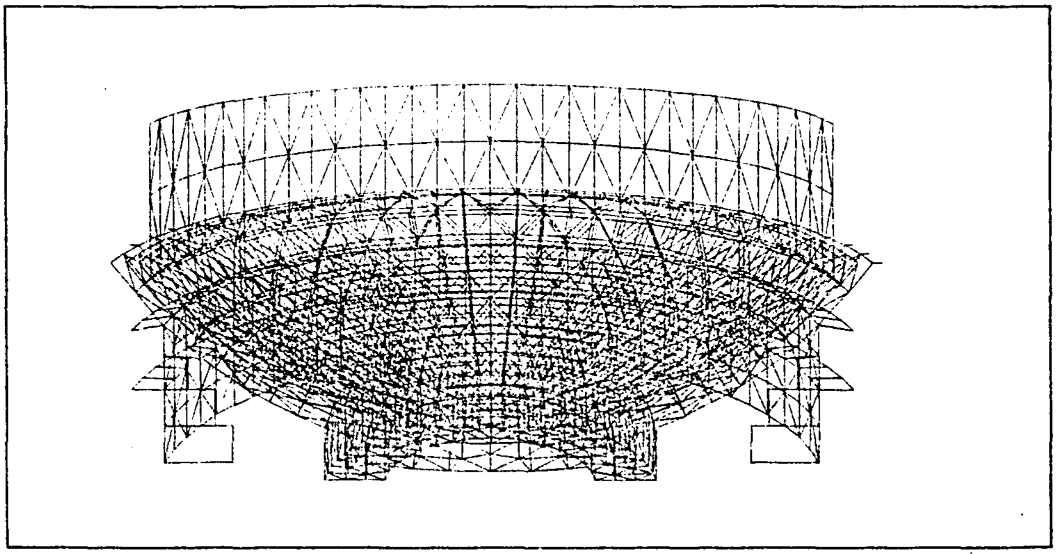

Fig. 3. Model for the analysis of the spherical cap.

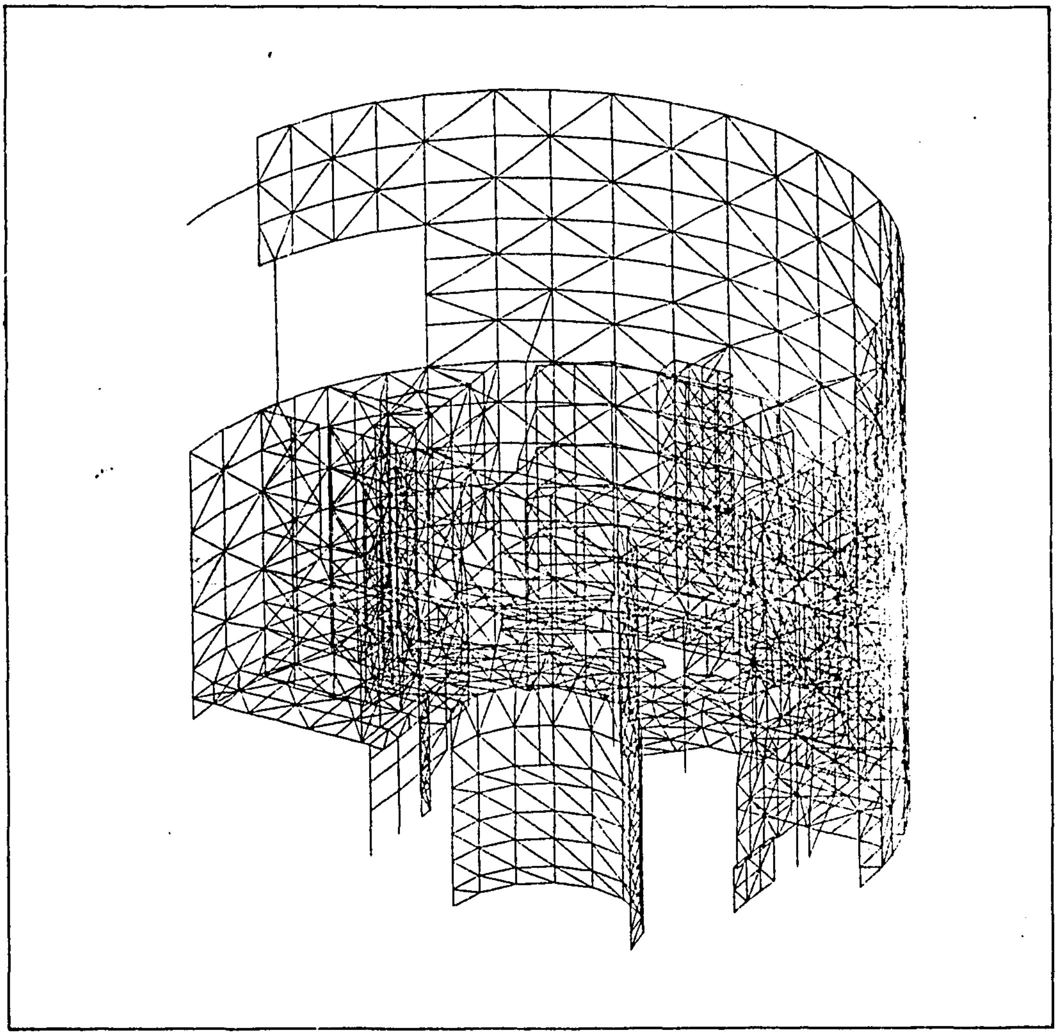

Fig. 4. Model for the analysis of the internal structures of the UJA part.

as long as the ratio of the two reinforcements is not known. The procedure for determination of the top and bottom reinforcement in an optimized way is rather simple and can be easily implemented in the postprocessing programs.

Due to the construction steps the reinforcement must be determined for a part of the structure. Since the reinforcement must be maintained constant over a delimitated part of the structure, due to constructive reasons, again a new procedure must be run, in order to find which is the critical reinforcement for all the investigated combinations and all the prescribed elements, which correspond to the structure part with the same reinforcement.

ORGANIZATION OF THE COMPUTER PROCEDURES

In order to be possible the management of all model data, load input, analysis results, combinations of forces, reinforcement determinations, critical reinforcements, and so on, it is necessary to build a system of data bases, over which the different programs are processed. The Figure 5 shows how the data bases are organized and how the different programs act with them.

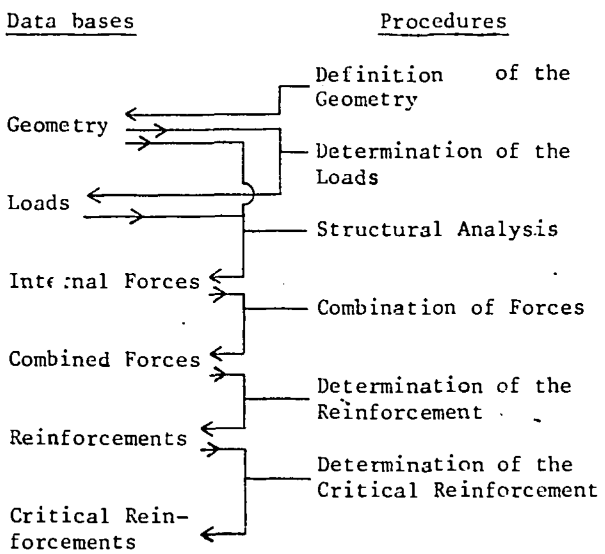

Figure 5. Organization of the design procedures and data bases.

It should be emphasized that the handling of the data must be made in binary code and never in a format code. That means that all the disk and tape files are binary files.

ATTAINED ECONOMY IN THE DESIGN DUE TO THE INTEGRATED MODELS

An economy in the design of Nuclear Power Plants can be achieved through the method outlined herein. The reasons will be clarified.

The individual structural elements of a Nuclear Power Plant are subjected to large local forces acting directly over or in the proximities of these members, i.e. the critical loading case for a particular element is due to a single loading combination. For all the other loading cases the reinforcement is understressed. For another structural element usually another loading combination is critical. Therefore there exists a rather great strength reserve in the building elements. If an integrated model is utilized, the acting forces will be more equally distributed, diminishing the local stresses due to the local acting forces. More members will participate transferring the acting forces to other structural parts. The integrated models cause in the analysis, a reduction of the forces in each element, and consequently the total reinforcement is reduced.

Comparisons of force determinations using integrated models and separated simple models have shown high discrepancies. In the analyses performed on simplified models without coupling, the forces in the elements are much higher.

DETAILING OF THE REINFORCEMENT

In the detailing of the reinforcement of the Angra NPP, several measures were taken in order to reduce the steel expenditure and to facilitate the construction at the site.

The utilized reinforcing steel has a yield strength of 500 MPa and an ultimate tensile strength of 550 MPa. In the heavy reinforced parts of the structure, bars with large diameter have been utilized such as 25mm, 32mm. In some parts 40mm diameter bars have been also used exceptionally.

For these large diameter bars the overlapping lengths are very large, causing installation problems and increasing steel expenditure. Therefore it was decided that, as long as it would be feasible, mechanical splices would be used. This causes as a consequence a reduction of the space occupied by the reinforcement and the concreting operations are easier done.

The spacings of the bars were also large in comparison with the usual practice. Spacings in the range of 30cm were used, for thick members and heavy reinforcement. In the case that the standards would not prescribe such large spacings, a skin reinforcement was used to distribute the cracking more evenly.

Another problem deals with the anchorage details of the large diameter bars. It is well known that the anchorage lengths of large diameter bars are very large. Since in the Reactor Building the large acting forces over the different elements are concentrated, especially over the anchor plates, the tensile forces in the reinforcement must be held immediately after the bar ends. In order to allow such force transfer, end anchor devices were attached to the bar ends by means of pressed anchorages, similar to the mechanical splices of the bars. The force transfers were undertaken in a very adequate way allowing a reduction of reinforcement in some critical anchorage areas.

DESIGN AND QUALITY ASSURANCE

The use of integrated models has allowed an optimization of the design work and also the control check of the calculations. The calculations are transparent due to the clear print outs of the results. The results are presented always in tabular form so that a good overview of the analysis and reinforcement determination can be achieved.

It has been proved that engineers could easily understand the intricacies of the design without much internal training in the project. The design engineers could then concentrate most of their time on the actual engineering work and not on devising simplifications for the determination of the internal forces of the elements. Of course some local work in the analysis was necessary but the overall behavior of the structure was thoroughly investigated by the large models.

In some cases the large models could not achieve sufficient detailing, since the mesh in some parts was quite rough. In these few cases, additional modeling was necessary.

The following procedure was undertaken in these cases. An area was delimitated, in which a finer mesh was necessary. A new local model was created in the interior of this region, maintaining however the same boundary points. From the large model results, the displacements were read for each important load case. These same displacements were imposed at the border of the local models together with the acting loads in the interior of the investigated region of the local model. This approximation could be easily checked, since the nodal forces should be the same for both models at the borders.

CONCLUSIONS

The technique of using large integrated models in the design of nuclear power plants was treated. This design method has numerous advantages in relation to the usual method in which the structural parts are treated with help of small models. A few advantages have been obtained:

a - a reduction in steel expenditure in the reinforced concrete members
b - a more transparent design method
c - a more reliable force determination of the structural elements, through a better representation of the structure
d - a larger number of investigated loading cases
e - a more organized calculation method
f - the possibility of using optimized steel reinforcement determination through design procedures.
g - reduction of the quality assurance work due to the clear automatic calculations.