AN APPROACH TO IDEALIZATION AND DESIGN OF DIAPHRAGM ELEMENTS IN NUCLEAR ISLAND BUILDING

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ABSTRACT

RC Structural slabs, in complex structural systems like Nuclear Power Plant (NPP) Structures, apart from providing resistance to the usual out of plane loads, plays a significant role in resisting effects of seismic forces due to their high in-plane rigidity. They act as effective diaphragm elements in distributing the horizontal seismic forces generated. Further, the diaphragm elements aid in tying the different vertical elements into a single integrated structural system to resist effects due to body forces, like temperature, shrinkage and creep etc.

This paper deals with design of RC structural slabs in such structural systems under the action of both out of plane and in-plane diaphragm forces. A two-stage analysis and design approach, adopting sub-structuring technique, has been used for idealization, analysis and design of these diaphragm elements optimizing computational efforts and providing cost acceptable solutions while performing analysis and design of a large size structural system. The design issues are discussed with an illustrative example and the solution adopted for a Nuclear Power Plant structure under construction in India.

INTRODUCTION

The RCC structural systems in a Nuclear Power plant consist of column and beam frames in two orthogonal directions forming a three dimensional framed structural system. RC walls may also form part of the structural system to cater to the functional and structural considerations. The RC walls act as the shear walls in the structural models to resist effectively the seismic forces. The 3-D structural models include modeling of the raft and soil springs along with the super structure to account for soil structure interaction effects. The floor slabs, idealized as part of the structural system, are inadequate for use in floor design. The idealization is generally adequate to cater to the functioning of the element as a diaphragm for lateral forces. At this stage, a fine mesh idealization is not practical due to the large size of the problem that needs to be catered to, and limitations exist to the degree to which the floor can be modeled based on the available information at this stage. It is therefore necessary to adopt a two stage approach for the analysis and design of such structural elements. In this paper, aspects related to idealization of floor slab and beam system and its analysis and design are discussed with an illustrative example.

The first stage of the two stage analysis and design methodology involves, FE modeling of the entire Structural Building system in which the slabs are idealized as pure diaphragm elements resisting only in-plane diaphragm forces. The floor slabs are modeled relatively coarsely to represent the diaphragm action with the availability of information on cutouts idealizing the major ones at this stage. This reduces the computational time and speeds up the structural analysis and design with information as appropriate at this stage. In the next stage, refined analysis of slabs is performed for the out-of-plane loads, by modeling the slabs separately as sub-structures, isolated from the main model. The results of the two stages of analyses are combined, and the design forces are obtained for the slab elements for the combined action of in-plane and out of plane forces. Based on the design forces thus obtained, the design of the slab is performed.

The methodology is elaborated with the example from the work being done for the Prototype Fast Breeder Reactor (PFBR), under construction, at Kalpakkam, in India. The Nuclear Island Connected Building (NICB) is a large Reinforced Concrete Building of size 92.6m x 83.2mx72m height consisting of eight buildings connected monolithically. Examples in this paper are derived from analysis performed for NICB of PFBR.

EVOLUTION OF ADOPTED METHODOLOGY

Floor slab systems perform following functions.

a) Support gravity loads due to floor finishes, partition walls, equipment and pedestals, false ceiling, loads to due to cable tray supports, pipe and duct supports etc.
b) Resist seismic forces in vertical directions acting on the self weight and mass of all elements supported by the floor slab
c) Acts as a diaphragm, between connected frames and shear walls integrated into the structure, providing in-plane rigidity. Diaphragm action ties the vertical elements of the structure together, under loads causing volumetric expansion / shrinkage of the structure. (E.g. Thermal loads causing thermal expansion of the structure).

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The structural idealization of floor system should cater for the following.

a) Enable appropriate evaluation of the out of plane forces in the floor system consisting of RC Slab and RC Beams due to the gravity loads.
b) Enable appropriate evaluation of out plane forces in the floor system consisting of RC Slab and RC Beams under seismic excitation in vertical direction.
c) Enable appropriate evaluation of in-plane forces in the floor system consisting of RC Slab and RC Beams under seismic excitation in both the horizontal directions including accidental torsion effects.
d) Enable appropriate of in-plane forces in the floor system consisting of RC Slab and RC Beams due to secondary effects on account of volume change due to temperature change or shrinkage and creep effects, especially in case of very large size structure.
e) Enable appropriate evaluation of in-structure response spectra for the floor slabs to facilitate seismic qualification of secondary systems supported on the floor slab.

The major constraint in idealization of the floor slab system is the availability of all information at the time of global analysis of RC structure. Following information is usually not available at the time of global analysis.

a) Location and size of opening / cutouts in the floor slabs as required from equipment considerations, as well as routing of services such as piping, cabling and ducting.
b) Piping analysis reactions under seismic excitation which are dependent on the in-structure response of the global model.

In the absence of all openings / cutouts, secondary beam layouts can not be finalized, which is essential for floor structural analysis and design. This invariably necessitates a two stage analysis and a design approach.

Two types of models are in vogue for global analysis of the structure.

a) A stick model of the entire structure representing the stiffness of the structure at different levels, and mass appropriately lumped at different levels and,
b) A full 3-D elastic model of the structure with beams and columns idealized.

Stick model with relatively lesser Degrees of Freedom is adopted for performing dynamic (seismic) analysis of the structure. The 3-D model is used for the purpose of static analyses. For seismic loads, the deformations of the stick model are imposed on the 3-D FE model, and pseudo-static analysis of the 3-D model is performed. While this reduces the computational efforts for dynamic analysis, this assumes that the slabs are “Fully Rigid”, (with infinite rigidity). In the idealization of the 3-D structural system as a stick, the floor system undergoes a rigid body rotation about the centre of stiffness which implies that the slabs are infinitely rigid.

3-D elastic models with the beams, columns and structural walls are idealized and the floor slab elements are modeled to represent its in-plane rigid behavior. For the NICB, a single 3-D model was used for both static and dynamic analyses simulating in-plane rigidity of the floors; Floors for detailed analysis and design are modeled as sub-systems.

METHODOLOGY ADOPTED FOR SLAB ANALYSIS AND DESIGN

Stage 1

Figure 1 showing a typical slab, isolated from the main structural model. The arrangement of the primary beams necessary for the modeling in the global analysis and the secondary beams necessary for resistance to out-of-plane loads are shown. The slab panels are also indicated.

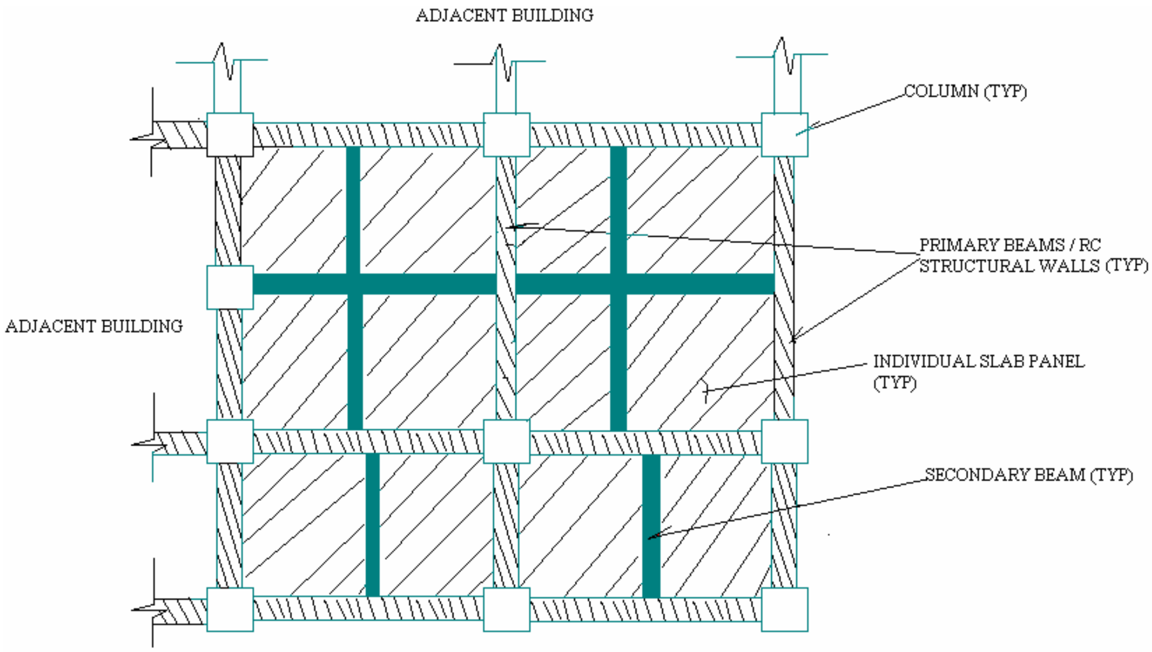

Figure 1: Layout of a Typical Sub model of Floor, Indicating Primary and Secondary Beams, Slab Panels, Shear Walls and Columns

Only the primary beams and columns/shear walls, forming the primary framework for the entire integrated structure, are modeled. The secondary beams are not modeled at this stage. The static and dynamic characteristics of the soil are idealized at the base of the structure in the form of bed of springs. The primary beams are designed based on the results of first stage analysis of integrated structural model. The slab panels are modeled, in the first stage, only to represent the in-plane effects, and the in-plane seismic and thermal forces in the slab elements are determined based on this analysis. Forces generated in the slab elements due to creep in concrete and initial & drying shrinkage of the structure are also considered.

The general layout of the NICB structure, with 8 buildings integrated and sectional view are furnished in Figures 2 and 3. The integrated structure consists of two concentric peripheral shear walls of about 800mm and 500mm thickness. These walls continue up to a height of about 14-16m above the raft, i.e., up to EL 30000. The elevation at the top of the base raft is EL 12000 mm. Containment walls of RCB (which is the central building among the eight integrated buildings), of about 1100mm thickness, form the next set of major shear walls, continuing up to the top of RCB (up to EL 84000) . The RCB is the tallest building of the integrated structure. Internal RC walls of the structure also act as shear walls, resisting the lateral forces generated in the structure.

A framework of columns and beams is provided in the peripheral zones of the structure above EL 30000, with the exception of the RCB zone, which forms the central zone of about 36m x 41m.. The proportion of lateral shear forces resisted by columns and beams are relatively low as the major shears are resisted by the shear walls.

The entire structure stands integrally tied, by means of RC slabs provided at different levels. These slabs act effectively in distributing the horizontal seismic forces among various vertical members, integrating the entire structure. Certain slabs (e.g., the slab at EL 30000) connect all the eight buildings, and are of size about 92.6m x 83.2m. In certain other levels, based on functional needs, the slabs connect only one or two buildings.

Under volumetric expansion / contraction of the structure due to thermal and other body forces like creep, these slabs tie the different parts of the structure and in turn have tensile / compressive forces (Figure 4). For lateral loads under seismic condition, the slab elements are subjected to in-plane tensile / compressive and shear forces.

This analysis yields in-plane forces in the slab elements, and the design forces for the primary beam elements are obtained.

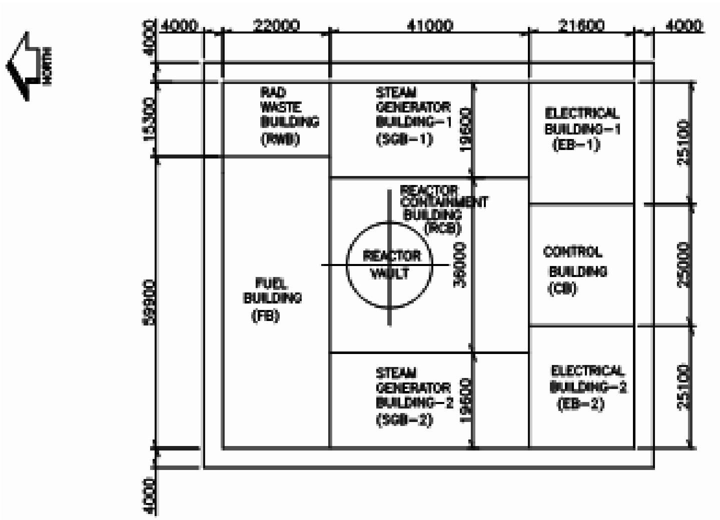

Figure 2: General Plot Plan of NICB

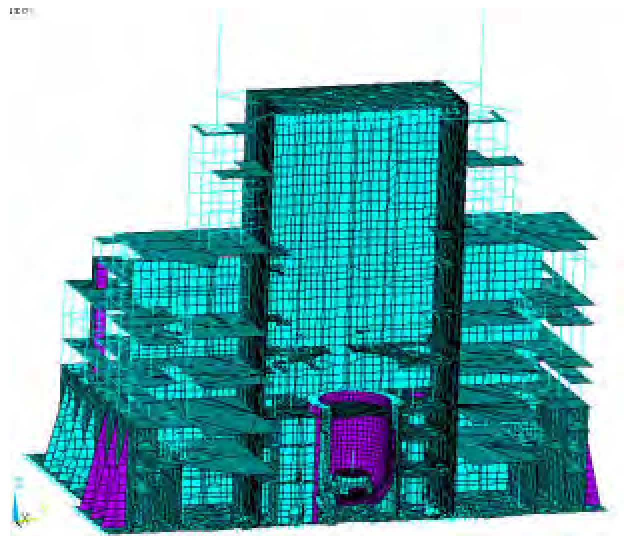

Figure 3: Cross Sectional view of 3-D Model NICB

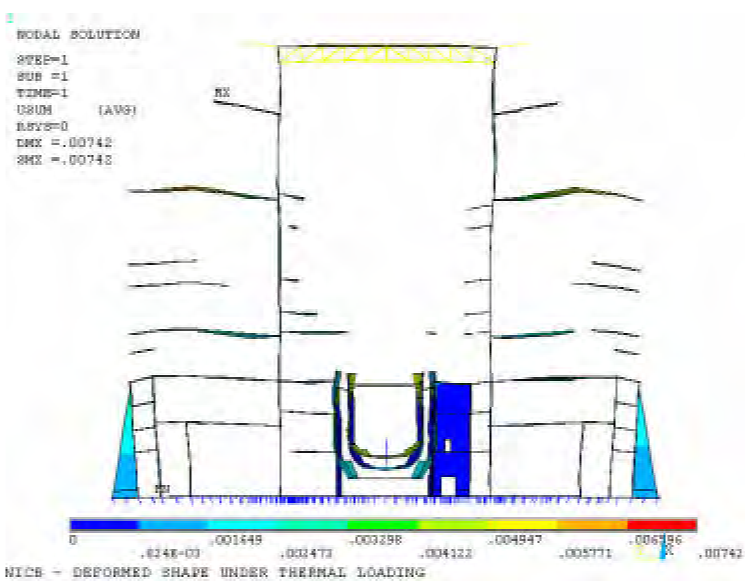

Figure 4: Deformed Profile NICB under Thermal Loads

Stage 2

The second stage analysis is a substructure analysis for the floor slabs. Secondary beams are modeled along with refined models of the slab panels with floor openings. The principal load that needs to be considered in this refined model is essentially vertical loads and effect of seismic excitation in direction out of plane of the floor. Appropriate evaluation of the response due to seismic excitation in direction out-of-plane of the floor panel can be made only with this refined model with secondary beams. Essential steps are as under:

a) For a typical floor, the portion of secondary beam framework covering a single building, isolated from the adjacent buildings by means of either primary beams, or shear walls, is considered. (Figure 1). The boundaries of the isolated sub-models, are formed by either primary beams or shear walls, which are stiff enough to prevent transfer of any displacement / forces from adjacent portion of the slab into the isolated part considered. The columns and walls below and above the floor are considered in the substructure model. Fixed boundary conditions are applied on the columns, at half the floor height above and below the slab portion considered. Secondary beams are added around all the openings of considerable size. An appropriate guideline for this provision is when the diameter or equivalent diameter of the opening is greater than four times the thickness of the slab. Secondary beams are also provided to stiffen the slab panels wherever slab loading has concentrated heavy loading needing beams for distribution of such loading to the primary beams and the primary structural system. They are also provided to divide large panels to smaller ones provide relief in moments in the slab panels. Slabs are not idealized in the sub-model for secondary beams. Only the mass of the slab panels are considered and are lumped on the secondary beams. The out-of-plane stiffness offered by the slab elements, being very small, is neglected.

b) Loads on the floor slabs are applied in a more refined and detailed manner, as compared to that applied in the integrated model. These are applied at the appropriate location along with the magnitude to correctly represent the flexural behavior of the floor system.

c) To determine the seismic response due to vertical excitation, the masses corresponding to self weight of slab and secondary beams, and masses due to equipment and other services as appropriate along with appropriate proportion of floor live load are lumped on the secondary and primary beams, along their lengths. The free response analysis is performed on this model to determine the vibration characteristics.

d) Static analysis of the floor system is performed to evaluate the forces in the beams. The response due to vertical excitation is performed carrying out a response spectrum analysis using the vertical seismic Building wise Floor Response Spectra generated for different buildings of the integrated structural model. The spectra are determined for floors at different elevations, and for damping values of 0.5, 1, 2, 4, 5, 7 and 10%. The Floor response spectrum corresponding to the floor elevation considered for the isolated model is used. The out of plane shear and bending moments in the secondary beams are determined. The secondary beams are designed for these forces, with load combinations performed in line with the specifications of Safety-Related code AERB/SS/CSE-1.

e) Individual slab panels bounded by secondary beams / primary beams / walls are individually analyzed and designed. For this purpose, in a given floor, critical slab panels are identified based on their loading, size, location, and in-plane forces in the panel from seismic, thermal, shrinkage and other loads. Based on the boundary conditions, the moment coefficients are determined. For the flexural stresses in the slab panel due to vertical excitation, the fundamental frequency of vibration of the slab panels is assumed as that of the critical frequency of vibration of the secondary beam model of the isolated slab structural system and the corresponding vertical seismic acceleration is used for design.

In the above methodology, following assumptions are made:

a) The moments in the secondary beams and out of plane forces, due to lateral seismic loads are considered insignificant to affect design of secondary beams and slab panels. Design of primary beams and columns considers loads due to lateral seismic effects. The main structural frame work is formed by the primary beam-column and shear wall system, which resist the entire lateral seismic forces.
b) Beams and columns are modeled along their center lines, and minor offset eccentricities at the junctions of beams and columns are neglected unless they are predominant.
c) While performing static and dynamic analysis of the secondary beam system, in the out of plane direction, the out of plane flexural stiffness of the slab elements are neglected, and only the stiffness of the secondary beams are considered in the model. Only the mass of the slabs are lumped appropriately on the secondary beams. This leads to a conservative design for the secondary beams.

CIFIC CONSIDERATIONS RELATED TO ANALYSIS AND DESIGN OF DIAPHRAGM SLABS

Specific issues related to planning of services running through floors, construction sequence and design of floors are discussed below:

a) At initial stage of analysis and design, (analysis of integrated primary structure), location of all the openings required for the different services are not available. Hence the in-plane modeling of the diaphragm slab elements, involves idealizing the entire area of the slabs, with only the major openings modeled. Usually services, like pipes and cable risers, running between different floors of the building are routed along the walls, penetrating the slabs at their periphery. Hence major portions of the periphery of the diaphragm slabs are punctured due to the services running adjacent to each other. Such a situation should be avoided as far as practicable, while initial planning of the services, in such a way that, that openings are not clustered along the periphery as this situation reduces the in-plane stiffness of the slabs and consequent diaphragm action.

b) Initial drying shrinkage of concrete together with creep in concrete, becomes a critical criteria, governing the reinforcement provided, in case of slabs of large spans, like the ones envisaged in NPP. (Typically in the current context the slabs at EL 30000 spans across the entire integrated NPP structure, with overall dimensions of around 92.6m x 83.2m). To avoid heavy reinforcement due to shrinkage stresses in such large slabs, construction is done in segments. The different segments are constructed with chronological gap between them such that while major portion of initial shrinkage happens for a particular zone, as the adjacent zones are not cast, the restraints imposed on the shrinkage deformation of the slab concreted is deferred to a possible time extent enabling considerable reduction in the shrinkage stresses ..

c) Certain floors functionally require large column-free areas. However, the floors above may have intermediate columns which are supported on transfer girders. Such columns undergo sinking, depending on the deflection experienced by the supporting transfer girders. While analyzing such system two issues are to be addressed,

i. Loads from all above-level floors will get transferred to the transfer girder through the floating column supported by the girder, and as a result, the deformed profile of the girder, and in turn, that of the associated floor slab system, and the vibration characteristics of the floor slab system gets affected.

ii. The analysis results of all the above-level floors depend on the vibrations and deformations experienced by the transfer girder and the associated floor, as the supporting column sinks accordingly.

Under such conditions, all the above-level floors, along with the supporting floor, behave as a unit, and hence it is not appropriate to isolate each floor slab as a separate substructure. Hence all the relevant floor slabs are modeled together into a single integrated sub-structure, and the analysis is performed once-for-all for all the floor slabs in such cases.

EXAMPLE PROBLEM – ANALYSIS OF SLAB PANEL IN PERIPHERAL ZONE OF NIB

This example elaborates design of a slab panel located in the peripheral zone of NICB, covering building EB1 (Electrical building) (Refer plot plan – Figure 2, for location of EB1 in the integrated structure). Slab at EL 30000 (16m above the base raft), is considered.

General layout of secondary and primary beams on EL 30000 floor of EB1 is shown in Figure 5a. Beams 6364a (vertical beam below grid 23 and between grids R and S), and 6365a (vertical beam below grid 24 and between grids R and S), for example, are secondary beams, added to reduce the span of slab, as seen in the layout. Beams B6340, B6341 etc (between grids 24 and 25 in corridor area), are added on the periphery of openings. Beams B6322, B6319 etc (horizontal beams below grid 23 and between grids R-S), are added to support certain panels/equipments mounted on the floor.

Along grid Q, it can be observed that long openings occur in the slab puncturing a major portion of the peripheral zone of the slab. These are openings provided for routing piping and other similar services.

Static and seismic analyses are performed as elaborated in the methodology. Based on the seismic analysis performed for the integrated structure, the in-plane forces in the slab elements are obtained under horizontal seismic conditions. The slab panels are mapped on to the modeled slab elements of the integrated model, based on their locations, and appropriate in-plane forces acting in the different slab panels are obtained. For the current problem, accordingly, a T_x value of 274.02 kN, T_y of 48.23 kN and T_{xy} value of 1054.90 kN are obtained for the critical panel.

Vertical seismic analysis of the sub model of secondary beams is then performed. For the present problem, a fundamental frequency is 9.25 Hz. The moment acting in the slab panels and out-of plane shear force acting are calculated for seismic load due to a vertical acceleration, corresponding to the fundamental frequency calculated above, and for the vertical static loads. This moment, M_x and $M_{y,}$ is 25 kN-m.

The above forces and moments are calculated for a critical load combination, (1.4 DL + 1.6 LL + 1.6 Thermal load + 1.6 Seismic load). Seismic load represents 3 components of forces and moments due to SSE or OBE excitation combined in 100:40:40 manners.

The forces acting in the critical panel shall thus be tabulated as given below,

Table 1: Showing Critical Design forces for Slab Panels

SL No	Forces in Critical Slab Panel (Units in kN and m)				
	T_x	T_y	T_{xy}	M_x	M_y
1	274.02	48.23	1054.90	25	25

The slab panels are designed for the combined effect of out of plane moments M_x and M_y, and the in-plane forces T_x, T_y and T_{xy}. The reinforcement required works out to 1780 mm^2 along NS direction and 1625 mm^2 along EW direction of the slab. Without considering the effect of in-plane forces the reinforcement obtained in the panel are 360 mm^2 along EW and 360 mm_2 along NS directions (Minimum required as per codal provisions).

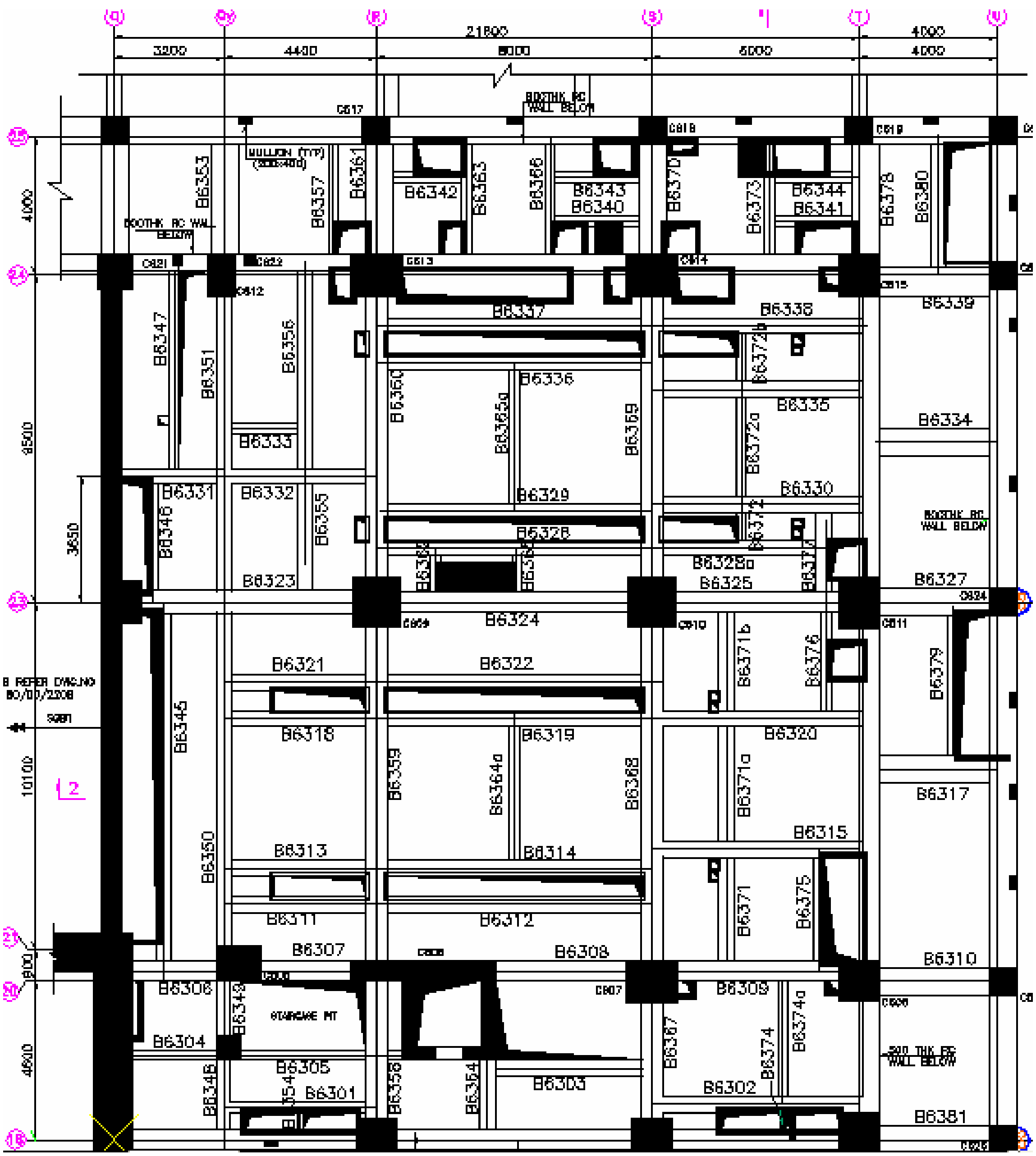

Figure 5a Layout of Primary and Secondary Beams in EB1 at EL 30000

CONCLUSION

Aspects to be considered while performing analysis of diaphragm slab panels in large structures, like Nuclear Power Plants, have been explained in this paper, with an example, considering a Nuclear Power Plant that is being constructed in India. A two-stage analysis methodology has been proposed to consider the effects of different internal forces and moments (in-plane and out of plane) that may get generated in the slab panels, and at the same time reducing the computational efforts in performing analyses. An example has been furnished. Based on the reinforcement results obtained with and without considering the in-plane forces for the floor slabs analysed and designed in this integrated structural system, it is concluded that in-plane forces generated in the slab panels form a major component affecting the reinforcement provided and has to be considered while designing the slab. The proposed methodology is suitable in considering the effects of above said forces, and giving acceptable solutions.

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