MAT FOUNDATIONS FOR SEISMIC RESISTANT BUILDINGS IN VENEZUELA

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SUMMARY

The two reinforced concrete cellular ribbed mats described in this paper were used as solution for the foundations of two seismic resistant reinforced concrete tall buildings built in heavy seismic zones of Venezuela. Both structures were designed by the author to withstand the seismic provisions prescribed by Venezuelan Seismic Regulations [1]. In both cases, mats were selected as foundation system for those buildings, as the best choice to accomplish their structural design with resistant soil conditions, dynamic responses and economical advantages. Built buildings are shown in Fig. 1 and Fig. 2. Other foundation solutions were also studied, but mats resulted the most advantageous. Lines of resistance of both buildings are reinforced concrete seismic resistant ductile frames placed regularly in two orthogonal directions. Structural system of resistant frames resists gravity and seismic loads acting on both structures.
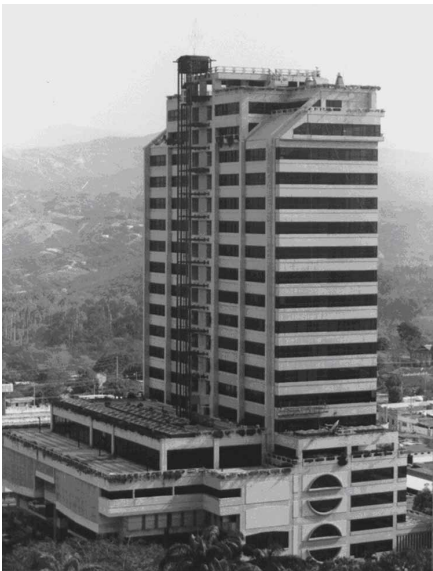
Fig. 1.   View of Building 80 meters high.

Fig. 2.   View of Building 60 meters high.

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INTRODUCTION

Building's cellular ribbed mats of both buildings were executed as it is usual for this kind of structural element: 1) by placing a bottom reinforced concrete solid slab in direct contact with the resistant soil stratum; 2) using reinforced concrete rectangular stiff ribs, orthogonaly placed in plan, forming an horizontal grid, whose axis corresponds to the structure upper axis in which are placed the resistant frames, (ribs were put inverted in these cases in order to set the bottom slab directly against the ground on a horizontal plane); and 3) by placing the upper reinforced concrete slab, supported on top of the inverted ribs, slab which in turn forms the lower floor basement of the building. These components made the mats stiff enough, giving excellent structural behavior and support to buildings. Vertical axis of building column's coincides and are placed at the intersections of horizontal mat ribs axis.

MAT BUILT EXAMPLES

First example. Rectangular Mat. Building 80 meters high.

Corresponds to the 80 meter high building shown in Fig. 1. It has a reinforced concrete seismic resistant structure, founded on a *rectangular* cellular ribbed mat of 21.60 x 50.75 meters. Bottom slab in direct contact with soil resistant stratum is 55 centimeters thick. Stiff inverted rectangular ribs of 2.50 meters wide by 2.60 meters high were placed in a rectangular grid with panels of 8.10 by 9.07 meters, dimensions which corresponds to the separation between structure's upper axis of the seismic resistant ductile frames. In Fig. 3. it is shown the schematic mat plan, and Fig. 4. shows its transverse section. Note in this figure the place and shape defined for the inverted rib construction joints. Building built in the 80´s has overcame minor and medium earthquakes events without any damages, it is located in Barquisimeto, Venezuela, city of intense seismic activity.
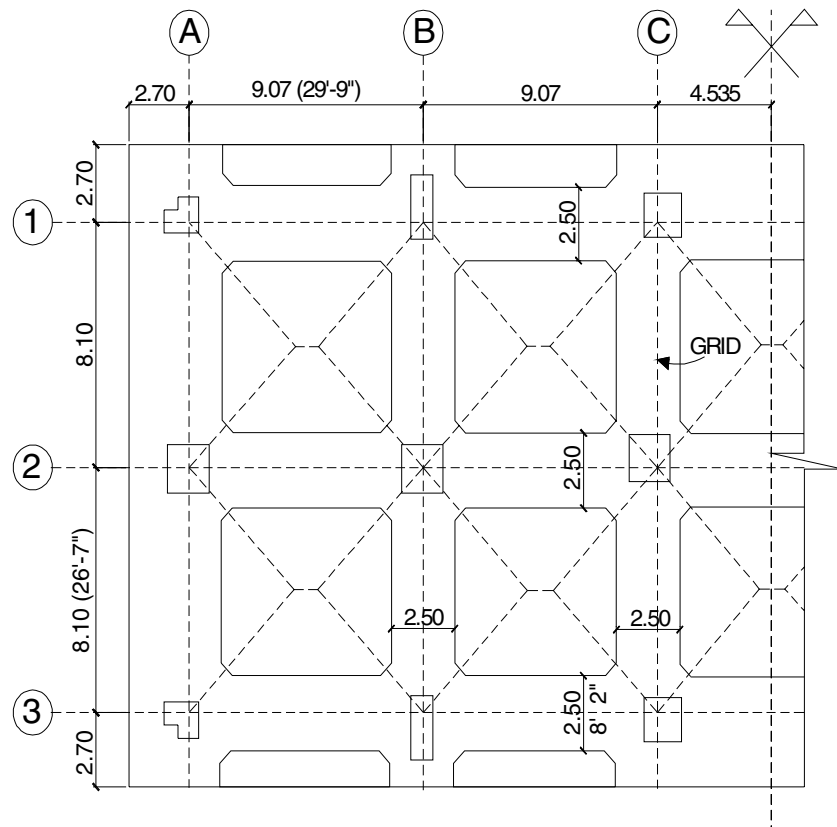

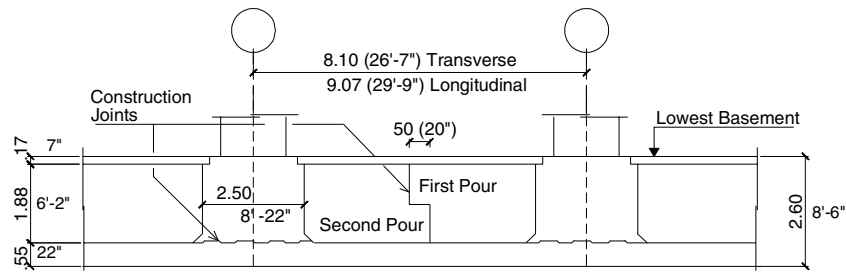Fig. 3.   Schematic plan of rectangular mat. Building 80 meters high.

Fig. 4.   Section of rectangular mat. Building 80 meters high.

Second example.   Square Mat.   Building 60 meters high.
Corresponds to the 60 meters high building shown in Fig. 2. It has a reinforced concrete seismic resistant structure, founded on an almost *square* cellular ribbed mat of 47.40 by 45.40 meters. Bottom slab in direct contact with soil resistant stratum is 60 centimeters thick. Stiff inverted rectangular ribs of 2.75 meters wide by 3.50 meters high, were placed in a square grid with panels of 10.60 by 10.60 meters, dimensions which corresponds to the separation between structure's upper axis of the seismic resistant ductile frames. In Fig. 5. it is shown the schematic mat plan and Fig. 6. shows its section. In this mat, some of the interior spaces (voids) between ribs and slabs were used as storage water tanks needed for the building operation. Building built in the 90´s, has overcome minor and medium earthquakes events without any damages, it is located in Caracas, Venezuela, city of intense seismic activity.
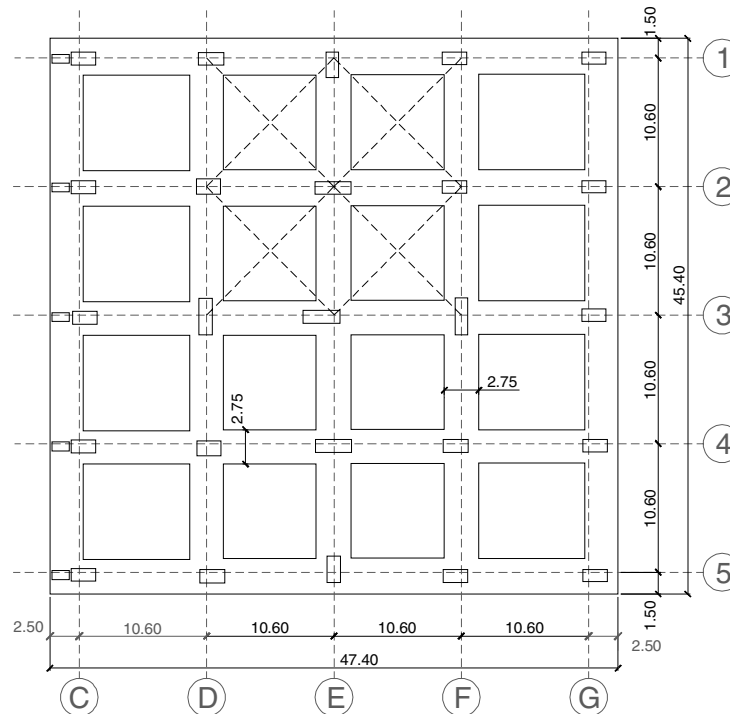

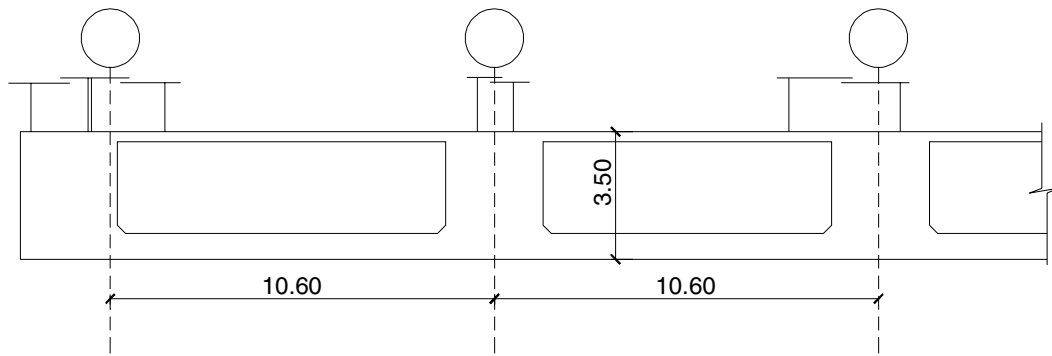**Fig. 5.   Schematic square mat. Building 60 meters high.**

Fig. 6. Section of square mat. Building 60 meters high.

MAT ANALYSIS AND DESIGN

Rigidity Conditions

The analysis of both mats were carried out assuming linear distribution of the soil reaction pressure, assumption justified in both cases by the high value of the soil coefficient of sub-grade reaction (soil reaction modulus) of more than 20,000 metric ton per cubic meter (1250 kips per cubic foot) and by the mat's structural stiffness. According to the procedure suggested by ACI Committee 436 (1966) [2], the value of "λ", as defined by the Formula Number 6 of that procedure, resulted in both cases larger enough than needed. Due to these structural properties, mat behavior in both building examples, were considered for analysis as rigid in both directions.

Structural Analysis

Conditions of equilibrium and geometrical compatibility of the entire mat were taken into consideration by means of a mathematical model that represented the grid formed by the orthogonal inverted ribs supported at their points of intersections with column vertical axes. Model considered full structural interaction in both directions between orthogonal stiff ribs.

To work out forces for design grid elements, the spans of the inverted ribs were loaded with an upward load equivalent to the tributary load on the panels that results when 45° diagonal lines are drawn in the horizontal plane from column centers at each panel, *rectangular or square*, between ribs. By this way, upward soil reaction load has a triangular or trapezoidal shape, whose maximum value is equal to the product of the height of the triangular or trapezoidal tributary load times the soil unitary upward reaction.

Basic Structural concept used for design

In the structural analysis some of the upward reactions of the grid at some of its nodes, resulted larger than column downward loads; meaning that the assumptions made for grid support at column axis, were valid for these nodes, but insufficient grid support were provided, at nodes where the upward reactions of the grid resulted lower than the downward loads of columns.

Fig. 7. Reinforcing steel of rectangular mat.

Fig. 8. Detail of inverted shear-key joint.

Structural Compatibility
In order to account for insufficient support at nodes where the grid upward reaction were lower than downward column loads, a new grid analysis was made, assuming the mat grid *supported only* at nodes where the grid upward reactions were equal or larger than the column downward loads. Each of the nodes with insufficient grid support was loaded with a load equal to the difference in that node, between the bigger downward load of column, and the lower upward reaction of grid. No other loads were considered in this compatibility analysis. Design forces for ribs placed at corners of the mat were particularly influenced by the result of this compatibility analysis. Structural components of the mats were designed for the superposition of the results of the two analysis described.

Nominal Pressures on the Soil. Rectangular Mat. Building 80 meters high.
The total weight of the building of first example -rectangular mat- is about 29,100 metric tons (64,100 kips), being the weight of the mat itself about 4,400 metric tons (9,698 kips). With this values the nominal uniform pressure transmitted to the soil is 30.56 metric tons per square meter (44 psi). When seismic actions are considered in transverse direction of the mat (shortest dimension), the nominal uniform pressure caused by the action of vertical loads changes to a maximum nominal pressure of 42.78 metric tons per square meter (61 psi) in one side of the mat, and to a minimum of 18.34 metric tons per square meter (26 psi) in the other side.

Nominal Pressures on the Soil. Square Mat. Building 60 meters high.
Nominal pressures on the soil exerted by building of the second example -square mat- resulted of the same order of magnitude that the pressures exerted by the building's mat of the first example.

Economic Considerations
When structural and soil properties permit the use of a mat instead of groups of high capacity piles as possible alternatives for foundations of seismic resistant tall buildings, the selection becomes a matter of economical advantages offered by each solution. Cost of caps, tie-beams and slabs needed for foundations integrated by piles, equals approximately the cost of an equivalent ribbed mat. In few words, the reinforced concrete elements of the two alternative solutions cost more or less the same. Differences which make mats economically favorable in many cases arise from the cost of the high capacity piles.
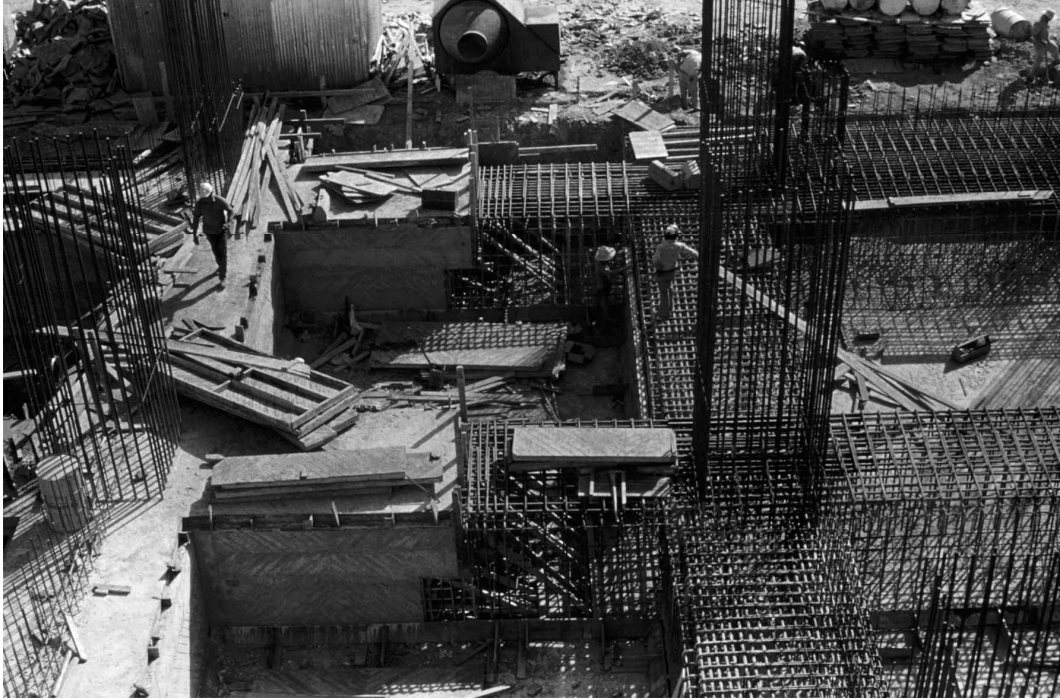
Fig. 9. Construction advancement rectangular mat. Note inverted shear-key joints. Building 80 meters high.

Fig. 10. Construction advancement square mat. Note inverted shear-key joints. Building 60 meters high.

CONSTRUCTION PROVISIONS

Mats dimensions called for special specifications regarding inevitable construction joints. In both mats the concrete of bottom slabs (55 or 60 centimeters thick) were poured in various operations doing appropriate upside-down shear-keys at center of panels, at each panel construction joint. The construction joints at the inverted ribs, were also selected at the center of some spans, using upside-down shear-keys of half depth of transverse section high of the ribs. Fig.8 shows in detail one built construction joint of this type in the rectangular mat (Building 80 meters high) and Figs. 9 and 10, shown where were the construction joints located in the rectangular and in the square mats.

Detailed upside-down shear-keys are needed in mat construction joints, their project and placement are of principal importance because soil reactions acts in up direction, and because ribs structural continuity requires that the second concrete pour in the construction joint goes downward the first concrete pour. In this way, the second poured part results really supported by the first one.

REFERENCES

[1]   Venezuelan Seismic Code. "*Edificaciones Antisísmicas*". Covenín 1756-87. Caracas 1988.

[2]   ACI Committee 436. "Suggested Design Procedures for Combined Footing and Mats". American Concrete Institute. Detroit, U.S.A.