STRUCTURAL ENGINEERING CONSULTANTS

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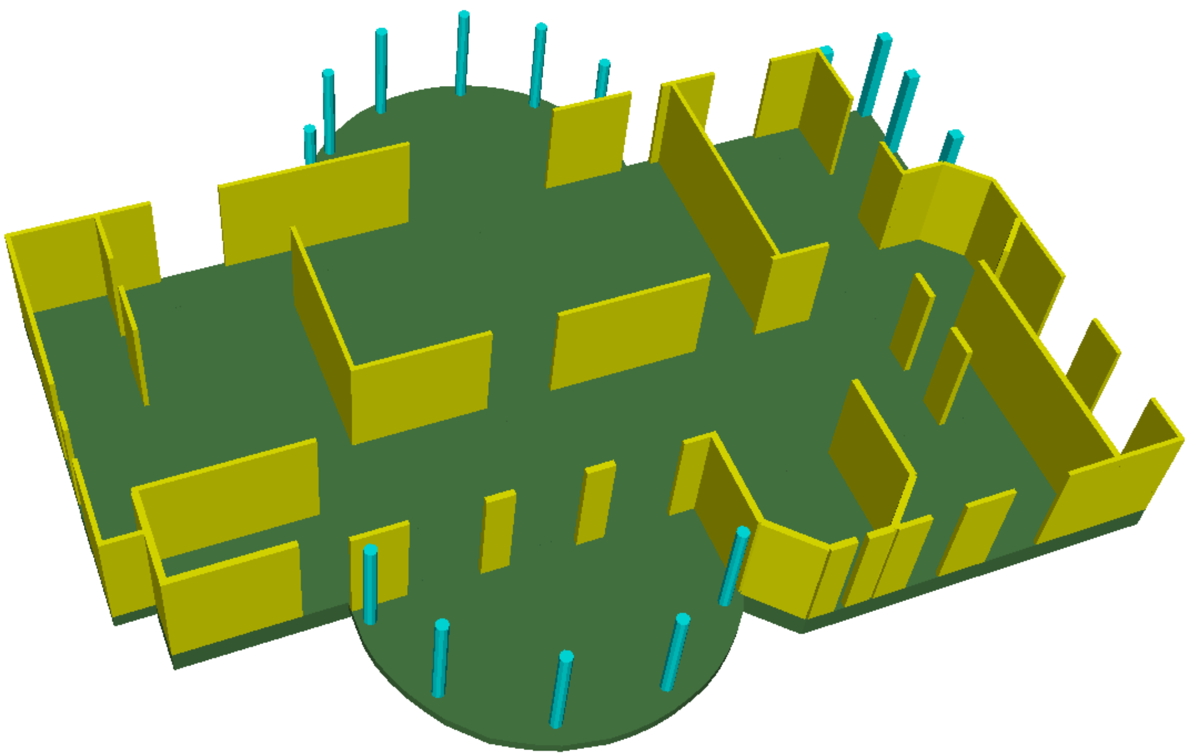
HILLCREST MANOR

Palo Verde, California

Structural Design of Mat (Raft) Foundation



First draft

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OVERVIEW

Hillcrest Manor is a low rise building to be constructed on soil with a low allowable bearing pressure. A conventionally reinforced mat (raft) foundation is selected, proportioned and designed, such as to spread the load from the walls and columns above over the entire footprint of the building. The objective of the design has been to distribute the load to a relatively uniform pressure not to exceed the allowable values of the soil.

The calculations presented herein cover the principal steps in the design of the mat (raft) foundation as it would be carried out in a structural engineering consultant's office. The difference being that many of the repetitive numerical reports generated by the analysis and design program used (ADAPT-Mat) are referred to, but left out for brevity without compromising the essential features of the work.

1 - STRUCTURE

The foundation mat (raft) consists of a contiguous conventionally reinforced concrete slab covering the entire footprint of the building. The top level of the mat is level. At locations of higher loads from above, such as below selective walls, the mat is thickened to achieve a more uniform distribution of pressure below the mat. Details of the mat configuration are reported in the section on "Geometry."

2 - MATERIAL

Concrete:

Weight	= 150 pcf
Cylinder Strength at 28 days for slabs	= 4000 psi
Modulus of Elasticity	= 4028 ksi
Creep Coefficient	= 2

Non-prestressed Reinforcement:

Yield Strength	= 60 ksi
Modulus of Elasticity	= 30000 ksi

Soil

Bulk modulus	= 150 pci
Allowable long-term pressure	= 2000 psf
Short term transient pressure	= 1.33*2000 = 2,667 psi

3 - DESIGN CRITERIA

3.1 Design Code

The design is based on ACI 318-2008; IBC 2009

3.2 Code Compliance Checks

The foundation mat (raft) is designed to meet the following criteria:

- Not to exceed soil pressure in sustained load condition
- Not to exceed soil pressure in transient load condition (earthquake)
- Design capacity for bending and shear exceeding design values (Ultimate Limit State)
- Punching shear capacity below column supports
- The available option in the analysis and design program for providing a minimum shrinkage reinforcement will not be invoked, since this is deemed not to be intended for RC mats.

3.3 Load Combinations

The applicable load combinations are reported in section 9.2

4 – GEOMETRY AND BOUNDARY CONDITIONS

The mat (raft) foundation is made up of a contiguous slab with overall dimensions 93.33 x 54.88 ft (Fig. 4-1). The mat thickness varies between 12 to 30 in. Slab bands of 30" thickness are provided below selected walls as shown on plan.

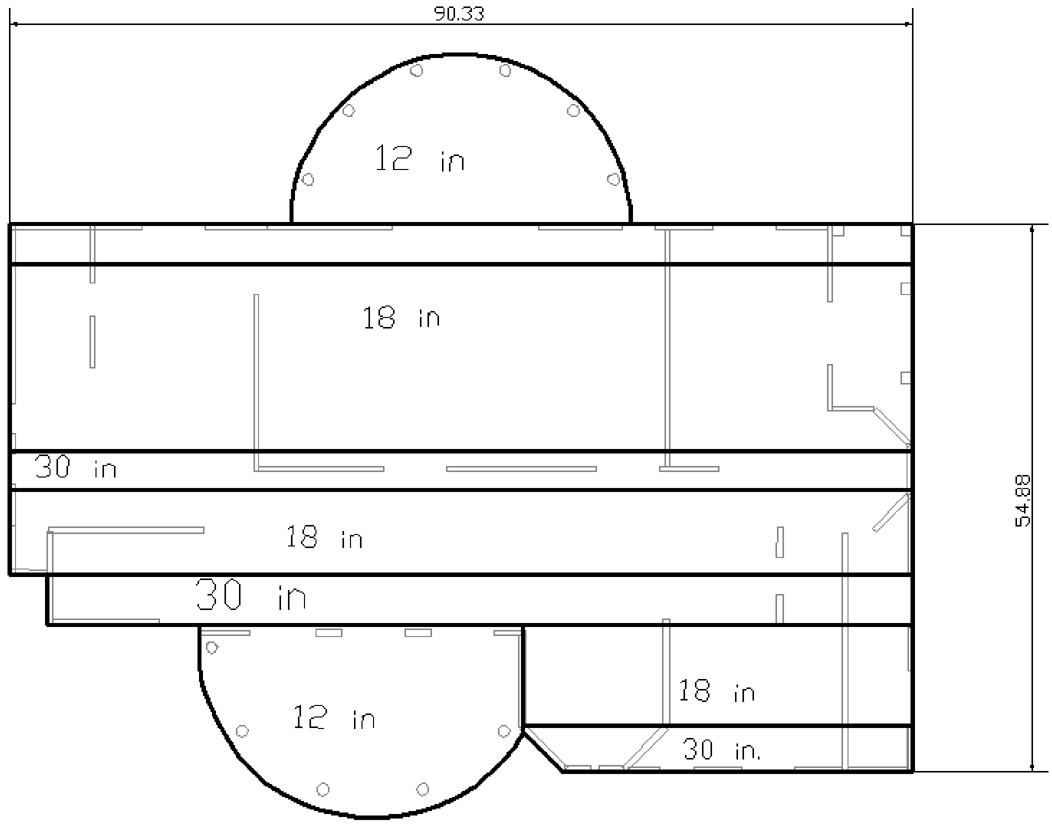


FIGURE 4-1 GENERAL LAYOUT AND DIMENSIONS

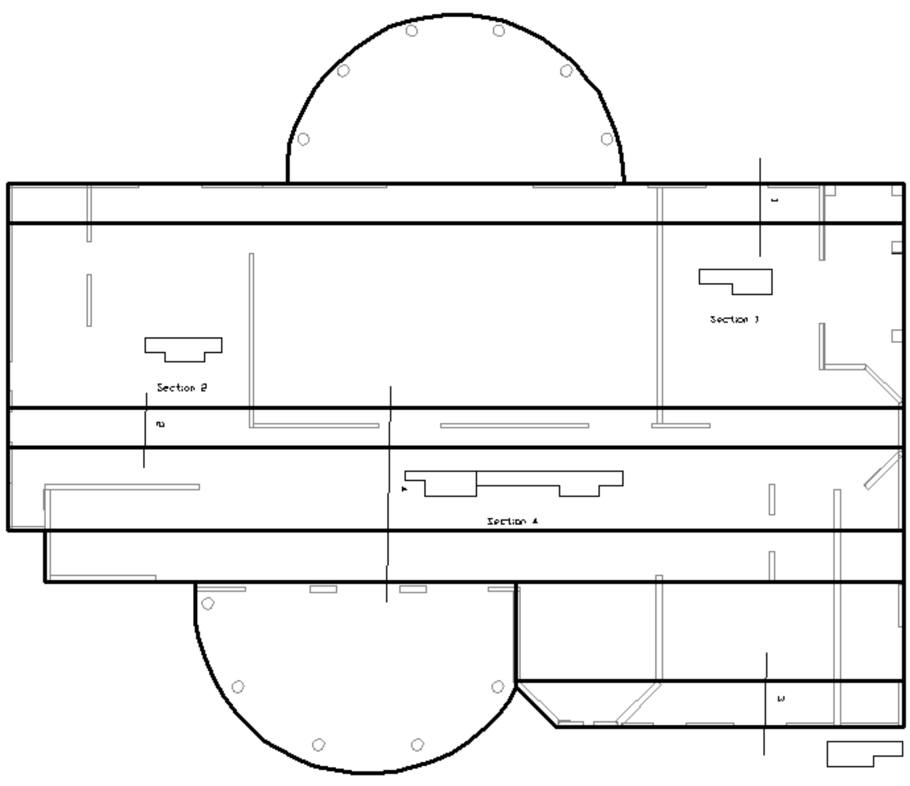


FIGURE 4-2 SECTIONS SHOWING CHANGE IN THICKNESS OF MAT

The structural model of the mat includes a level of walls and columns above the mat as shown in the 3D view of the analysis/design model (Figs. 4-3).

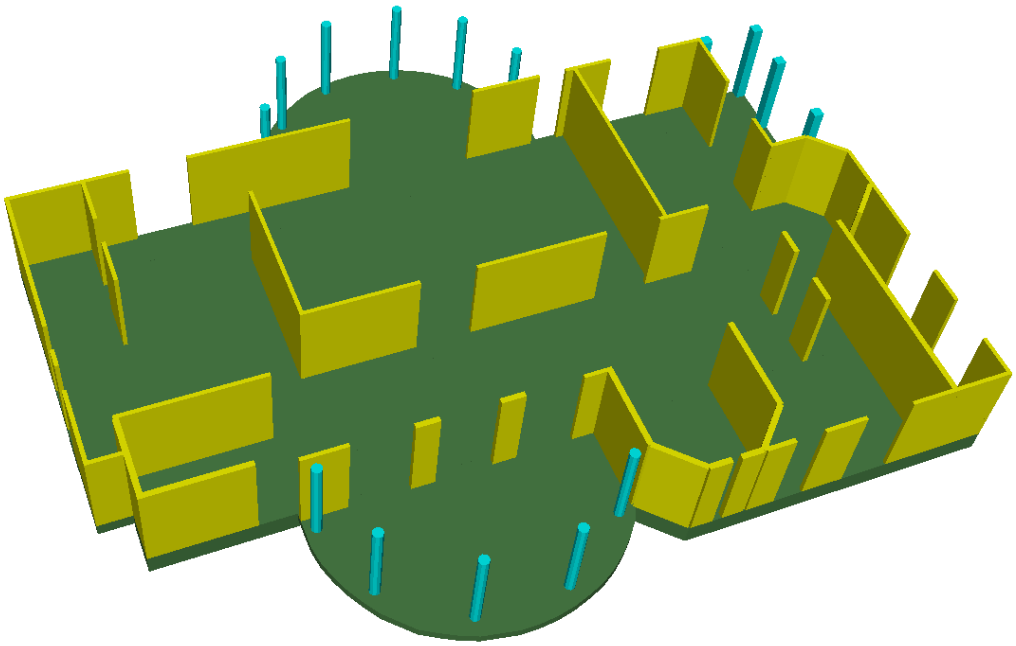


FIGURE 4-3 VIEW OF ANALYSIS/DESIGN MODEL THAT FEATURES ONE LEVEL OF WALLS AND COLUMNS ABOVE

5 - LOADS

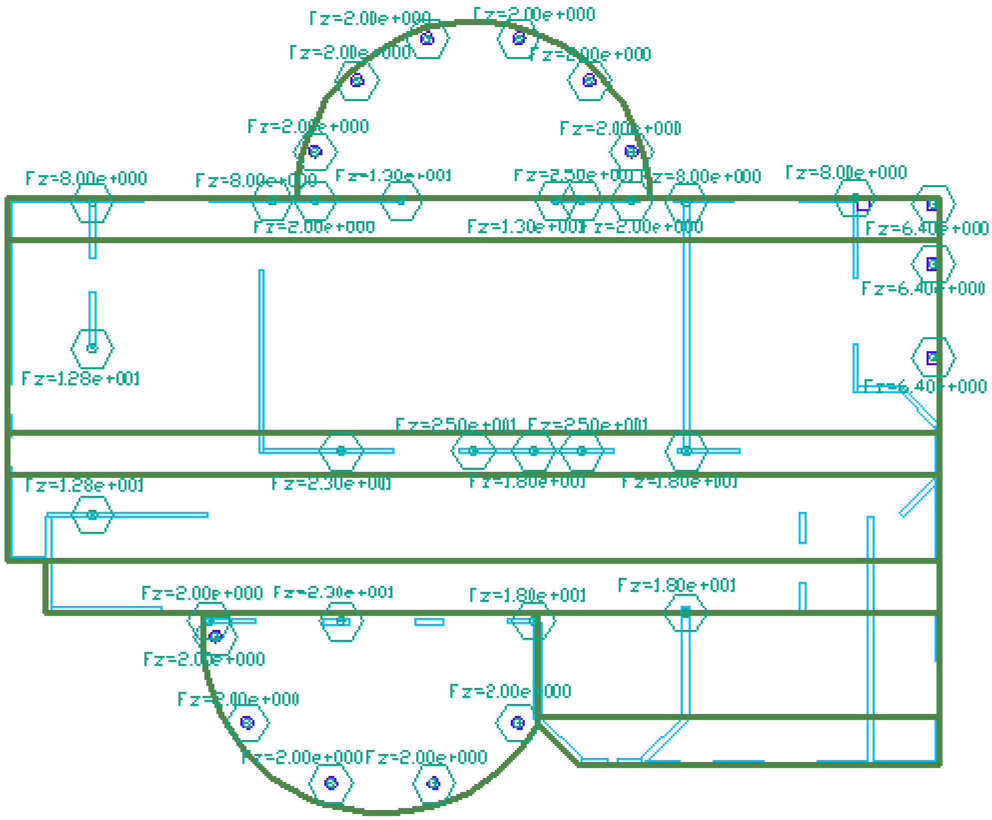
The loads on the mat consist of the following:

Selfweight (Selfweight)

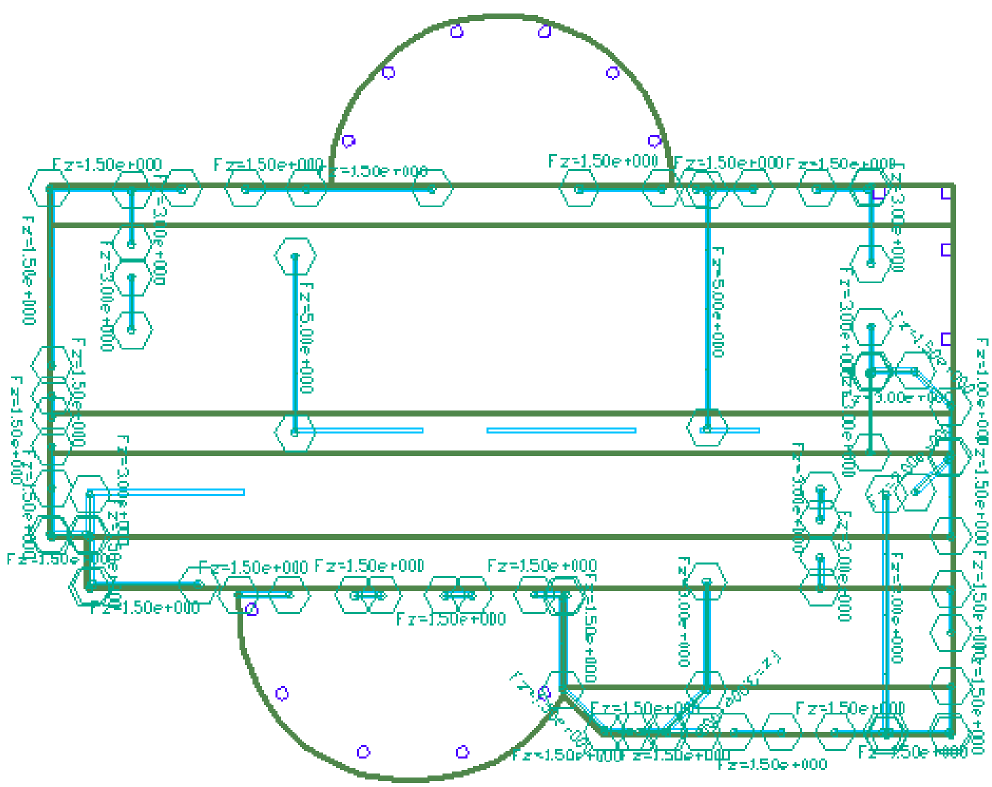
Based on concrete volume = 150 pcf

Dead Load (Dead load)

Consist of concentrated loads on top of columns, and
Line loads distributed on top of the walls. The dead load includes roof load. These are shown graphically in Figs. 5-1.



(a) Concentrated Dead Load (kip)

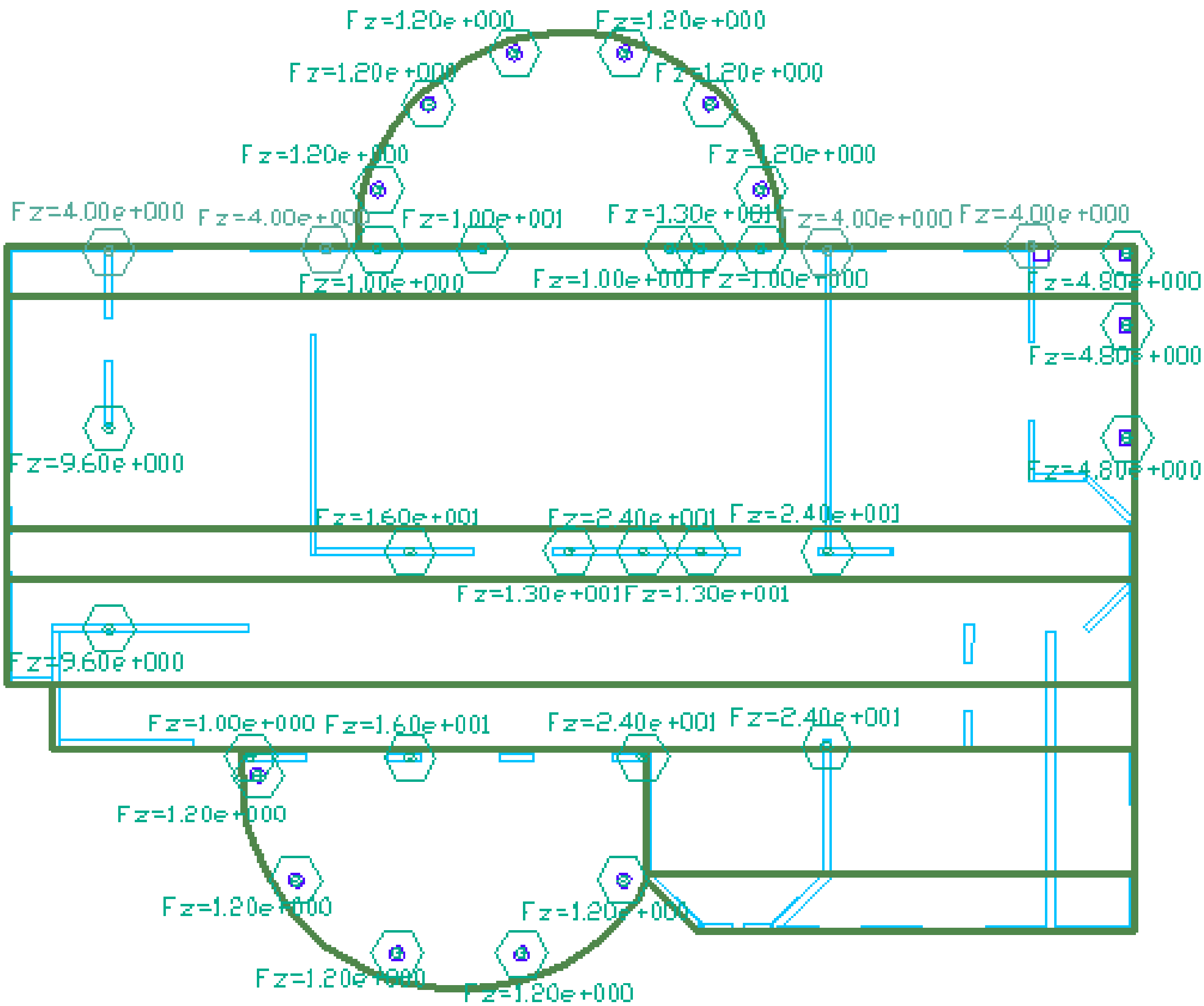


(b) Line Dead Load (k/ft)

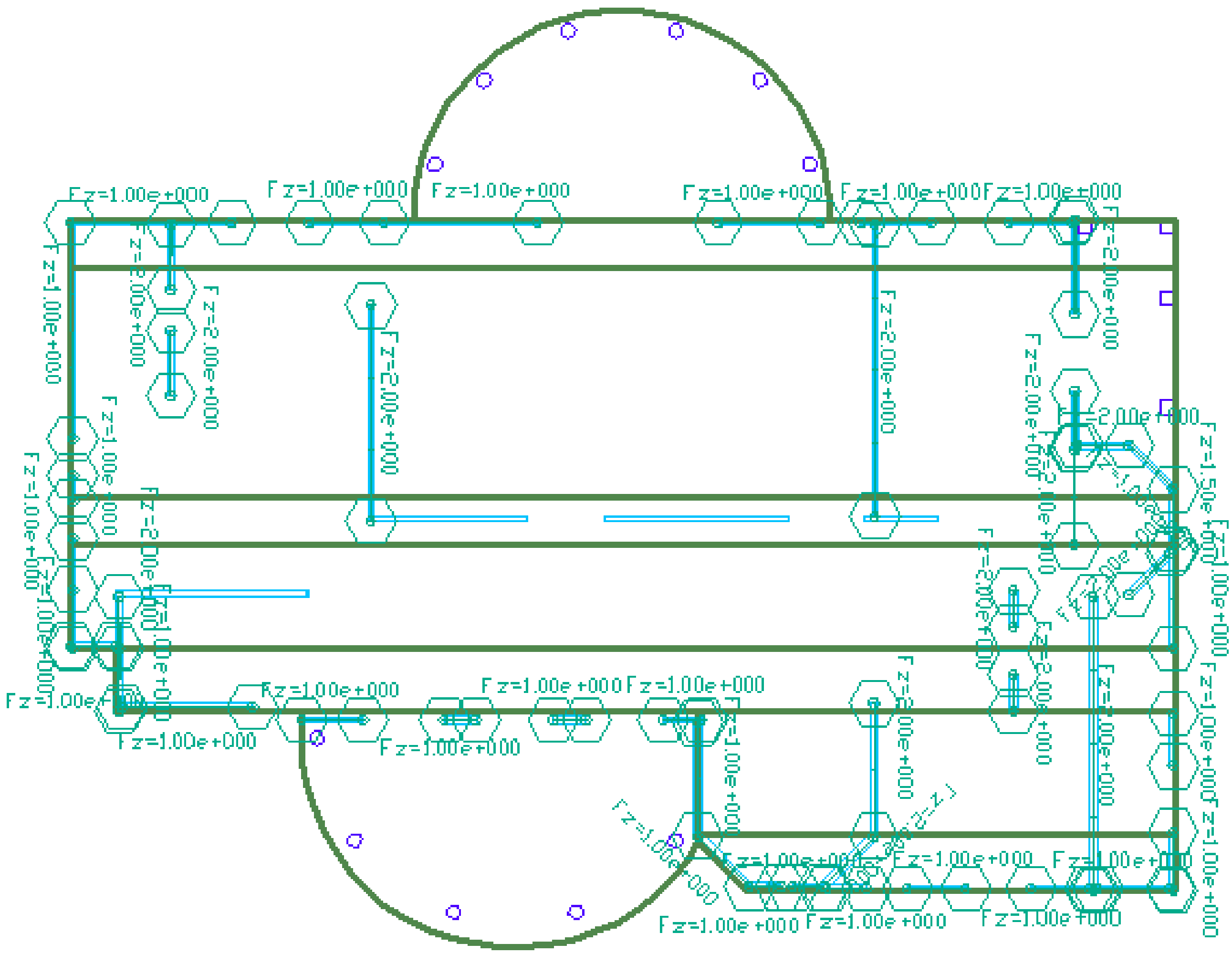
FIGURE 5-1 SUPERIMPOSED DEAL LOAD

Live Load (Live load)

- ❖ Distributed uniform load over the entire mat = 100 psf
- ❖ Line load at top of walls typically 2 to 3 k/ft as shown in 5-2



Concentrated Live Load(kip)



(b) Line Live Load (k/ft)

FIGURE 5-2 LIVE LOAD

Roof Live Load (Roof_LL)

- ❖ Distributed as concentrated loads over the columns and uniform line loads over the walls above the mat (see 5-3 for values)

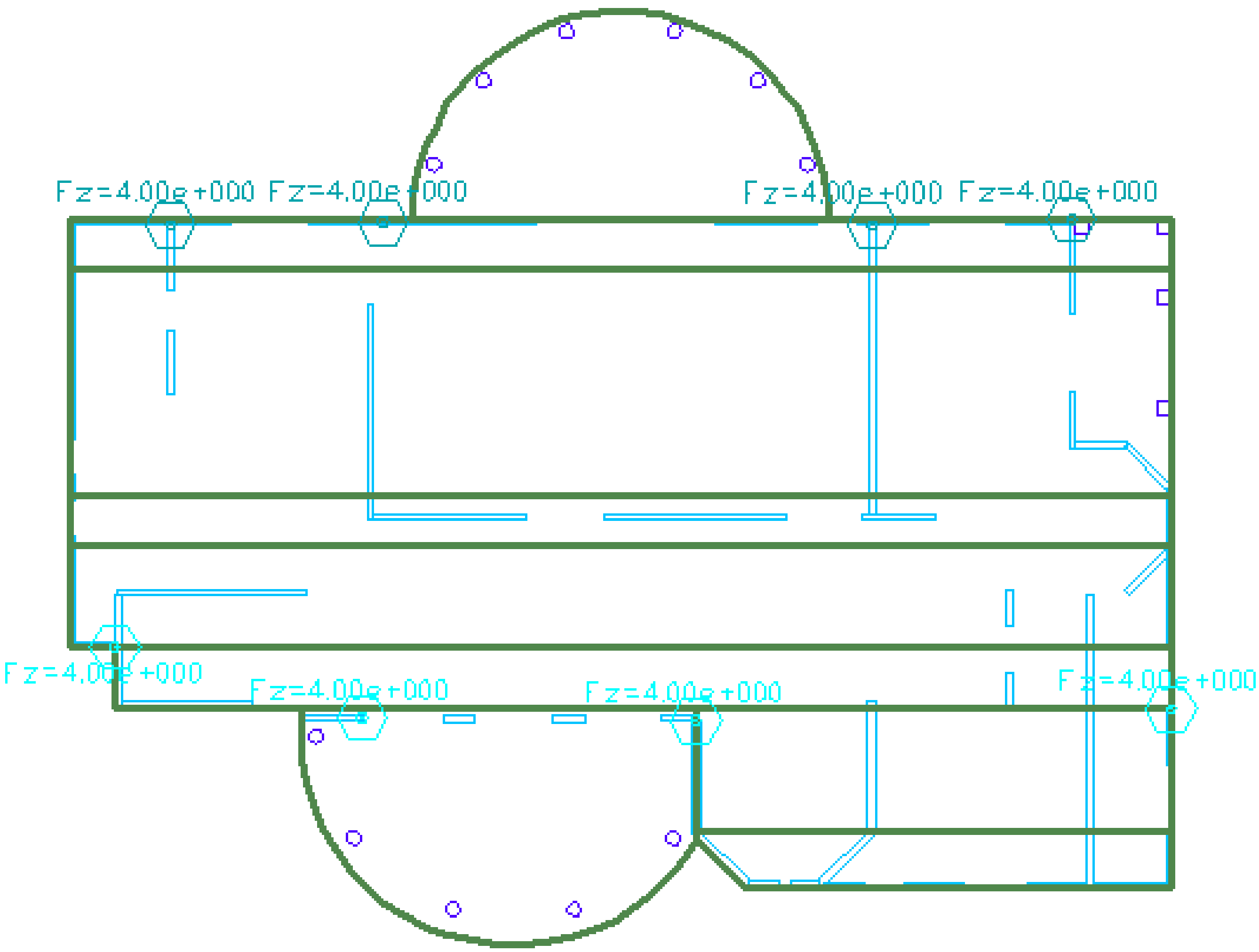
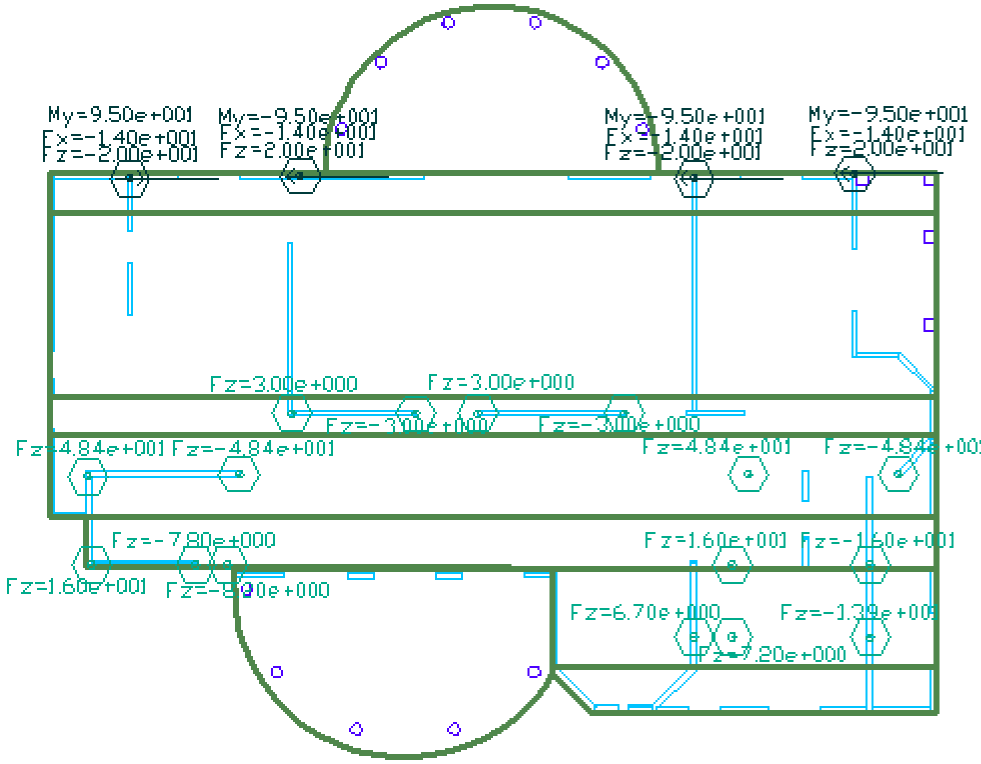


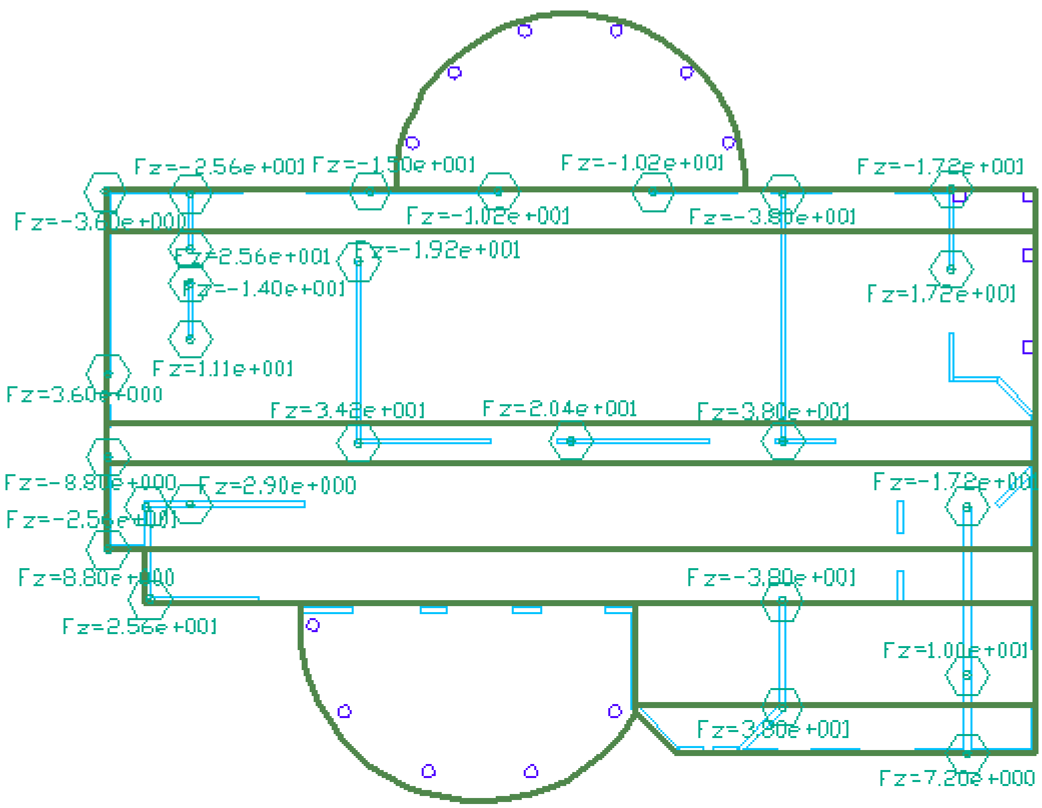
FIGURE 5-3 CONCENTRATED ROOF LIVE LOAD (kip)

Earthquake Loads

- ❖ Earthquake action in X-direction (along the long axis) (Load EQ-X, see 5-4a)
- ❖ Earthquake action in Y-direction (along the short axis) (Load EQ-Y, see 5-4b)



Earthquake Load in X-X direction (long-direction)



Earthquake Load in Y-Y direction (short direction)
FIGURE 5-4 EARTHQUAKE LOAD

6 – BASE REINFORCEMENT

Base reinforcement is the rebar placed in the mat at user selected locations prior to the analysis and design. The program will consider these as provided rebar, and will report the reinforcement that may be necessary for code compliance in addition to the user defined base reinforcement.

Bottom base reinforcement

#4 @ 12” o.c. along X-X (long direction) cover 3”
#4 @ 12” o.c. along Y-Y (long-short) cover 3.5”

Top base reinforcement

#4 @ 24” o.c. along X-X (long direction) cover 1” from top
#4 @ 12” o.c. along Y-Y (long-short) cover 1.75” from top

7– OTHER REINFORCEMENT

Reinforcement, where necessary to meet the design specifications and the governing code, will be calculated by the program and reported in amount, size, location and length. Refer to Section 11 for the design outcome and details.

8 - PRESTRESSING

No prestressing is specified. The mat is analyzed and designed as a conventionally reinforcement concrete structure.

9 - ANALYSIS

9.1 Discretization

Using ADAPT-Mat computer program, the structure is discretized in well proportioned quadrilateral finite element cells for improved results. All cell vertices meet at common nodes to guarantee the equilibrium of applied loads with the analysis results. The discretization used is shown in Fig. 9.1-1

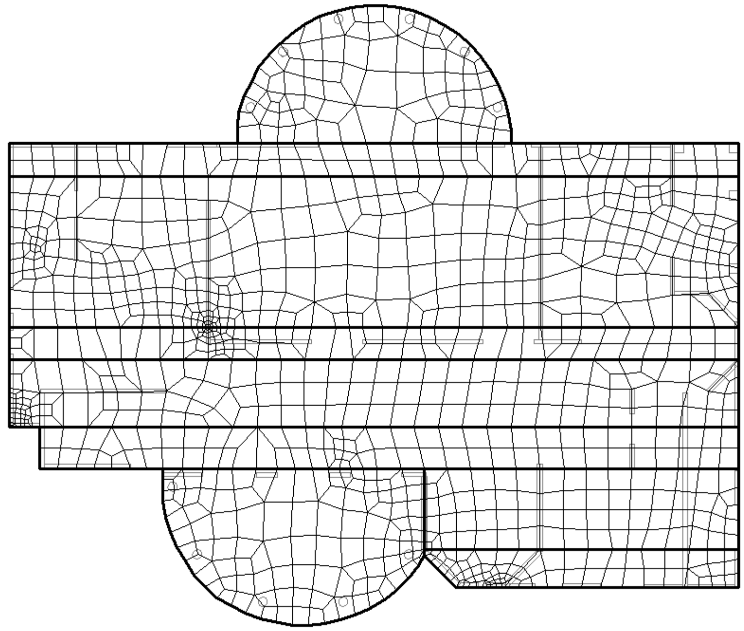


FIGURE 9.1-1 VIEW OF THE FINITE ELEMENT MESH USED FOR DESIGN

9.2 Load Cases and Load Combinations

The load cases and load combinations defined are reported by the program and reproduced below. The load combinations are automatically generated by the program, once the design code is selected. The user has the option to edit the program generated load combinations, however.

Each load combination is evaluated by the program for code compliance using one of the several building code required evaluation options. The default evaluation options of the program depend on the building code selected by the user. The evaluation option used by the program for each of the load combinations is reported preceding each load combination cases as noted below:

The evaluation options used for this project are:

- Service Total Load
  Reports deflections, actions (moments, etc) and associated minimum rebar, if needed beyond user defined base reinforcement
- Service Sustained Load
  Reports deflections, actions (moments, etc) and associated minimum rebar, if needed beyond user defined base reinforcement. This load combination is used for long-term deflection.
- Strength
  Calculates and reports rebar needed for strength requirements of the code, beyond what the user has defined as base reinforcement

Other evaluation options, such as cracked deflection are not used in this project. The following list of load cases and load combinations are excerpts from the program's reports for this project.

LOAD CASES
Dead load
Live load
Selfweight
Load EQ-X
Load EQ-Y
Roof_LL

LOAD COMBINATIONS
Name: Service(Total Load)
Evaluation: SERVICE TOTAL LOAD
Combination detail: 1.00 x Selfweight + 1.00 x Dead load + 1.00 x Live load + 1.00 x Roof_LL
Name: Service(Sustained Load)
Evaluation: SERVICE SUSTAINED LOAD
Combination detail: 1.00 x Selfweight + 1.00 x Dead load + 0.30 x Live load + 0.30 x Roof_LL
Name: Strength(Dead and Live)
Evaluation: STRENGTH
Combination detail: 1.20 x Dead load + 1.60 x Live load + 0.50 x Roof_LL + 1.20 x Selfweight
Name: Service_EQ_YY
Evaluation: SERVICE TOTAL LOAD
Combination detail: 1.00 x Selfweight + 1.00 x Dead load + 1.00 x Live load + 1.00 x Roof_LL + 0.70 x Load EQ-Y
Name: Service_EQ_XX
Evaluation: SERVICE TOTAL LOAD
Combination detail: 1.00 x Selfweight + 1.00 x Dead load + 1.00 x Live load + 1.00 x Roof_LL + 0.70 x Load EQ-X
Name: Strength_EQ_XX
Evaluation: STRENGTH
Combination detail: 1.20 x Dead load + 1.20 x Selfweight + 0.50 x Live load + 1.00 x Load EQ-X + 0.20 x Roof_LL
Name: Strength_EQ_YY
Evaluation: STRENGTH
Combination detail: 1.20 x Dead load + 1.20 x Selfweight + 0.50 x Live load + 0.20 x Roof_LL + 1.00 x Load EQ-Y
Name: Strength_09DL_EQ_YY
Evaluation: STRENGTH
Combination detail: 0.90 x Dead load + 0.90 x Selfweight + 1.00 x Load EQ-Y
Name: Strength _09DL_EQ_XX
Evaluation: STRENGTH
Combination detail: 0.90 x Dead load + 0.90 x Selfweight + 1.00 x Load EQ-X

9.3 Deflections

The deflection of the mat under the "sustained load combination" is given in Fig. 9.3

Name: Service(Sustained Load)
1.00 x Selfweight + 1.00 x Dead load + 0.30 x Live load + 0.30 x Roof_LL

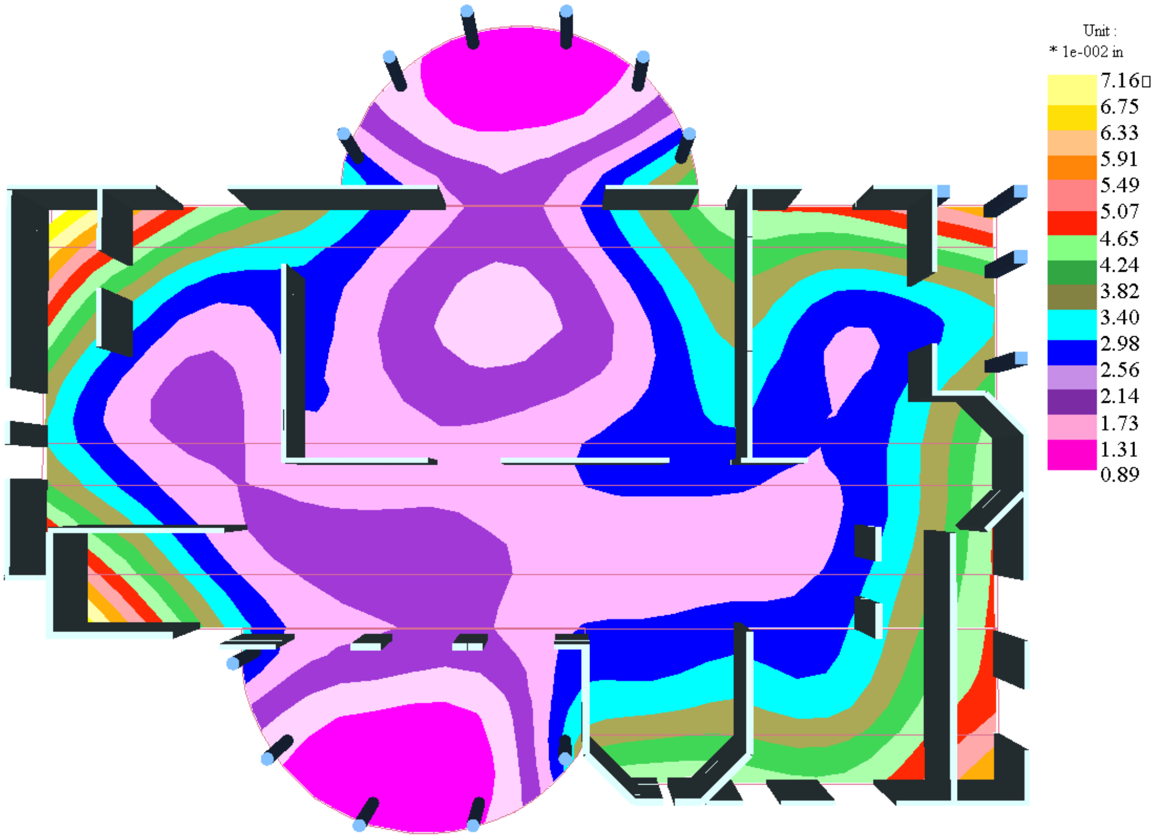


FIGURE 9.3-1 IMMEDIATE DISPLACEMENT RESPONSE OF THE MAT/SOIL TO THE SUSTAINED LOAD COMBINATION.
(Maximum immediate displacement = 0.07 inch)

9.4 Soil Pressure

Sustained Load Combination

The allowable soil pressure under sustained load combination specified is 2000 psf. The distribution of soil pressure for this load combination is given by the contour line diagram shown in Fig. 9.4-1. From the contour diagram, the maximum "point" pressure is at the top left corner of the mat. It is equal to"

$$0.0107 * 1000 * 144 = 1{,}541 \text{ psf} < 2000 \text{ psf (OK)}$$

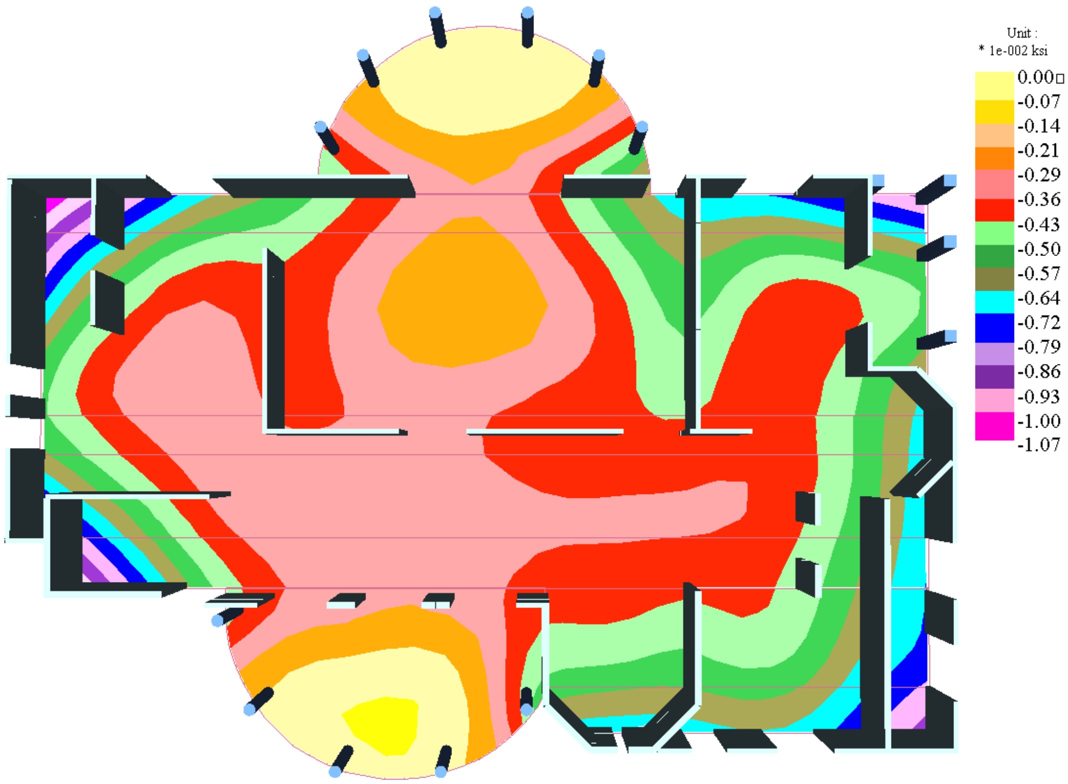


FIGURE 9.4-1 DISTRIBUTION OF SOIL PRESSURE BELOW THE MAT UNDER “SUSTAINED” LOAD COMBINAITON

Comment:
Strictly speaking, the allowable soil pressure does not apply to the pressure reported at a “point” in a contour plot, such as Fig. 9.3-1. The allowable soil pressure intended for the average pressure over a minimum area, such as a square or circle having a diameter or side value between three to four times the slab thickness. In the current design, since the point pressure is within the allowable value, the design is considered acceptable. Otherwise, using the pressure contour, the average pressure over the preceding minimum area would have had to be calculated and checked with the allowable value.

Transient Load Combination
The allowable soil pressure for the transient load combinations of wind and seismic actions is 2,667 psi. The governing load combinations in the current case are earthquake along X-X and Y-Y directions as given below:

Name: Service_EQ_XX
1.00 x Selfweight + 1.00 x Dead load + 1.00 x Live load + 1.00 x Roof_LL
+ 0.70 x Load EQ-X

Name: Service_EQ_YY
1.00 x Selfweight + 1.00 x Dead load + 1.00 x Live load + 1.00 x Roof_LL
+ 0.70 x Load EQ-Y

The analysis results indicates that the soil pressure for the load combination with earthquake along the long direction (X-X) is more critical. The pressure distribution is shown in Fig. 9.3-2. The maximum “point” pressure is:

0.152 * 1000 * 144 = 2,189 psf < 2,667 psi OK

Again, it is re-iterated that as in the case of gravity load case, the average pressure over an area with side dimension three to four times the slab thickness would have been selected to determine the average pressure for code compliance.

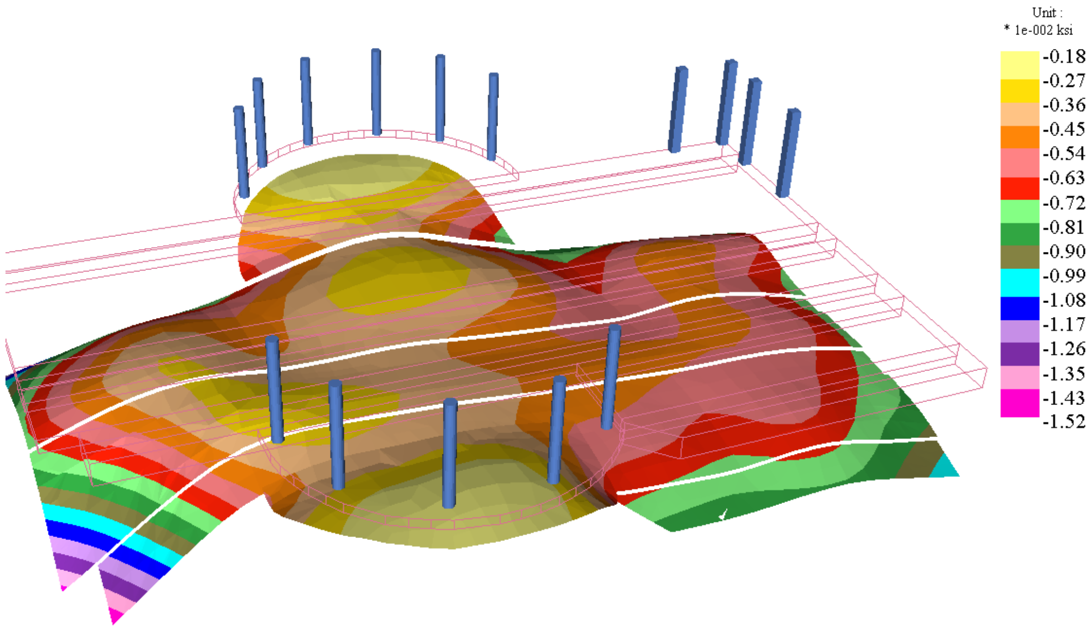
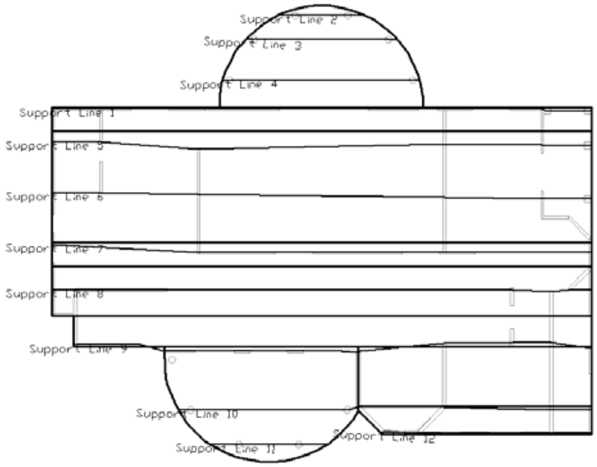


FIGURE 9.4-2 DISTRIBUTION OF SOIL PRESSURE FOR TRANSIENT LOAD COMBINATION (SEISMIC ACTION ALONG THE LONG DIRECTION X-X)

10 - DESIGN VALUES

10.1 Design Strips

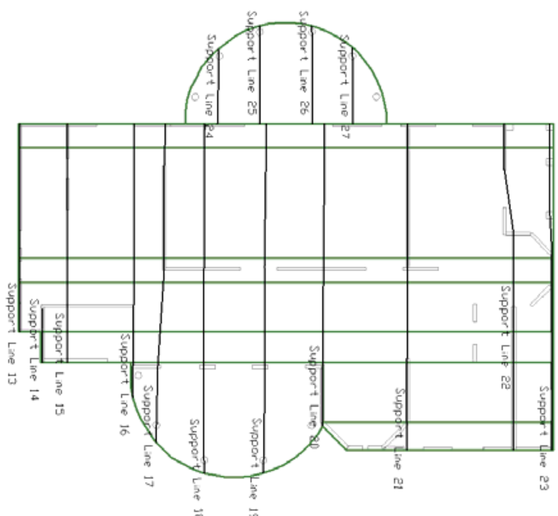
To obtain the design values (moments, shears, etc) for mat foundations the standard procedure of subdividing the structure into design strip in two orthogonal directions is applicable. Unlike the elevated conventionally reinforced slabs where the design strips are automatically subdivided into “column” and “middle” strips, for mat foundations the design strips typically extend between midpoint of adjacent columns/walls transverse to the direction of a design strip. The design strips are based on the support lines drawn in each direction. Figs. 10.1-1 and 10.1-2 illustrate the selected support lines and the associated design strips.



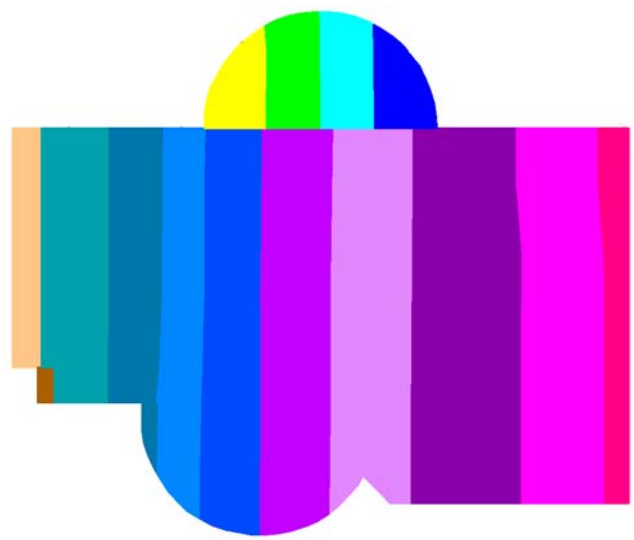
(a) Support line identification

(b) Design strips

FIGURE 10.1-1 DESIGN STRIPS IN THE LONG DIRECTION



(a) Support line identification

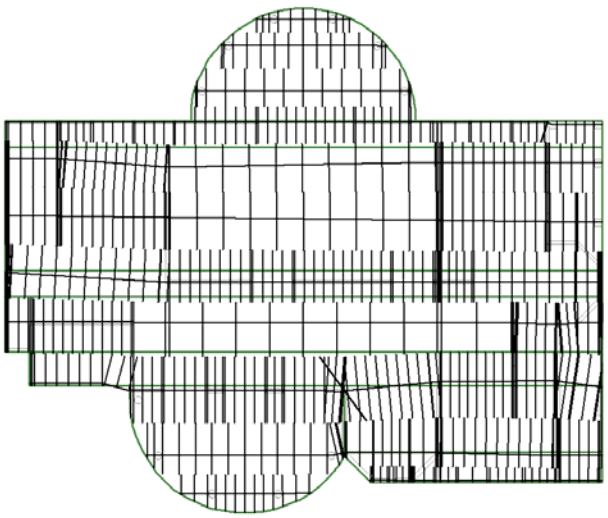


(b) Design strips

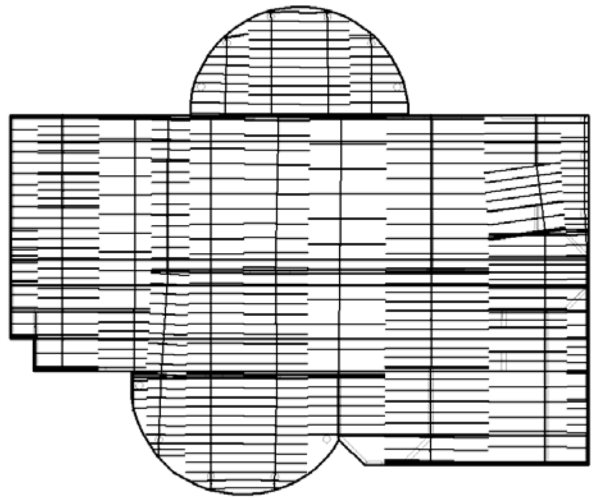
FIGURE 10.1-2 DESIGN STRIPS IN THE SHORT DIRECTION

10.2 Design Sections

For a complete design and code compliance check of the mat area, design sections are generated in two orthogonal directions over the entire surface of the mat. Design values (moments, shears, etc) are determined for each of the design sections. At the design stage to follow, the program checks the availability of reinforcement at each of the design sections and adds rebar, where necessary. Fig. 10.2-1 illustrates the design sections for each of the two principal directions.



(a) Design section for long direction



(b) Design sections for short direction

FIGURE 10.2-1 DESIGN SECTIONS IN ORTHOGONAL DIRECTIONS

10.3 Design Values

Moments, shears and other quantities obtained for each design section and each load combination are enveloped to obtain the applicable maximum and minimum values along each of the design strips. Figs. 10.3-1 and 10.3-2 show the distribution of the design moment envelopes for the two orthogonal directions. The numerical values for the design sections can be seen either graphically, or in tabular forms. For clarity, these are not shown in the figures.

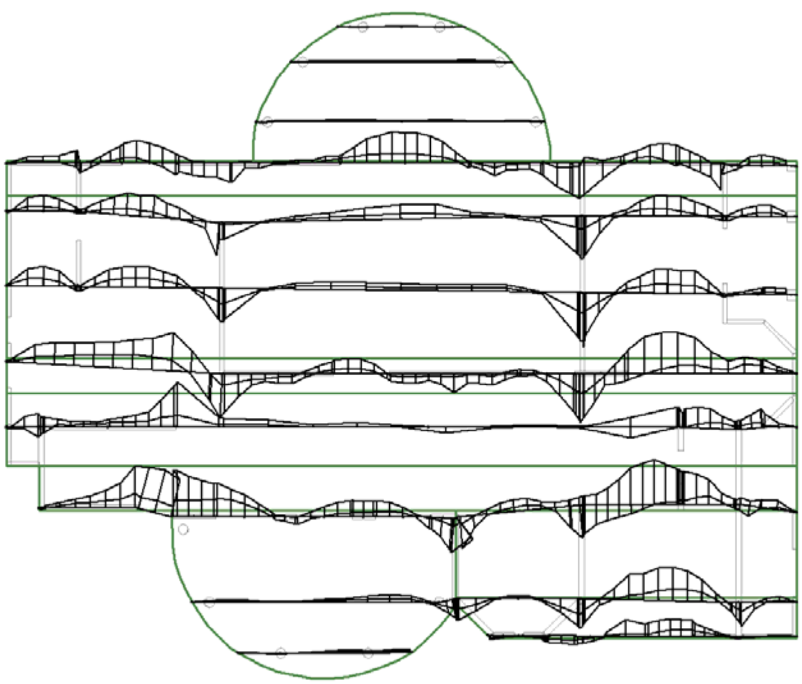


FIGURE 10.3-1 ENVELOPE OF MAXIMUM AND MINIMUM DESIGN VALUES FOR STRIPS IN THE LONG DIRECTION

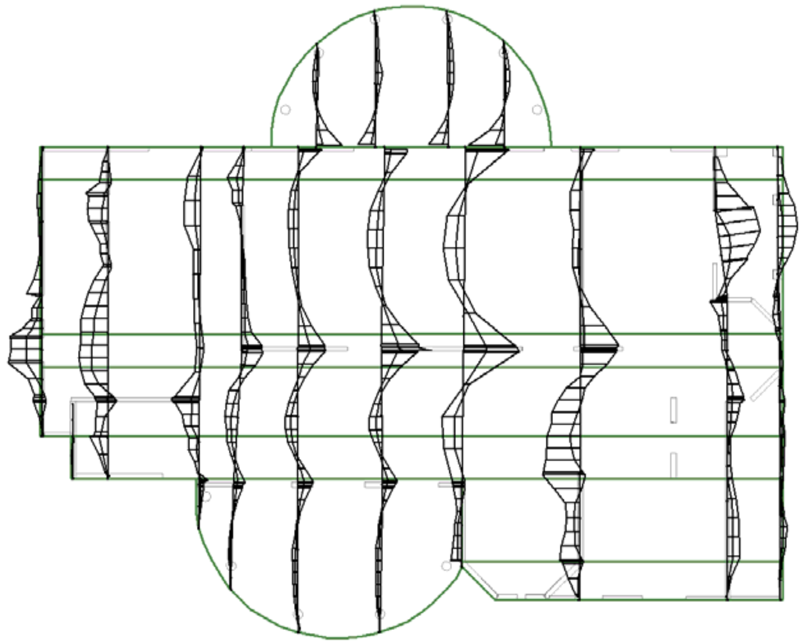


FIGURE 10.3-4 ENVELOPE OF MAXIMUM AND MINIMUM DESIGN VALUES FOR STRIPS IN THE SHORT DIRECTION

Tabular reports generated by the program give the design values of each design section for each load combination in addition to the envelope of all load combinations. For a sample, Table 10.3-1 lists the design values for a specific load combination and support line.

TABLE 10.3-1 TABLE OF SELECTED DESIGN VALUES[1]

Load Combination: Strength (Dead and Live)

Design Strip: Support Line 7

Design section	Moment	Shear	Axial	Torsion
	k-ft	k	k	k-ft
703000	70.808	15.907	2.650	-42.860
703001	44.006	17.211	4.768	-35.038
703002	25.163	4.269	7.389	-55.281
703003	21.172	-1.469	6.780	-44.694
703004	26.296	0.164	6.399	-51.795
703005	26.400	-1.063	6.138	-42.333
703006	6.434	17.184	1.404	-32.011
703007	-17.043	13.322	-1.307	-9.288
703008	-32.096	7.735	-4.075	-36.369

The envelope of maximum and minimum values from all the load combinations defined for each of the design strips is compiled in the graphical reports of each design strip. Fig. 10.3-5 illustrates this envelope for design strip 7. Negative values refer to tension at the top of the mat.

[1] In the Design Section identification column the first digit (7) refers to the support line, the third digit (3) is the number of span along the support line, the remainder of the digits to the right give the design section ID from the face of support at one end of the span to the face of support at the other end.

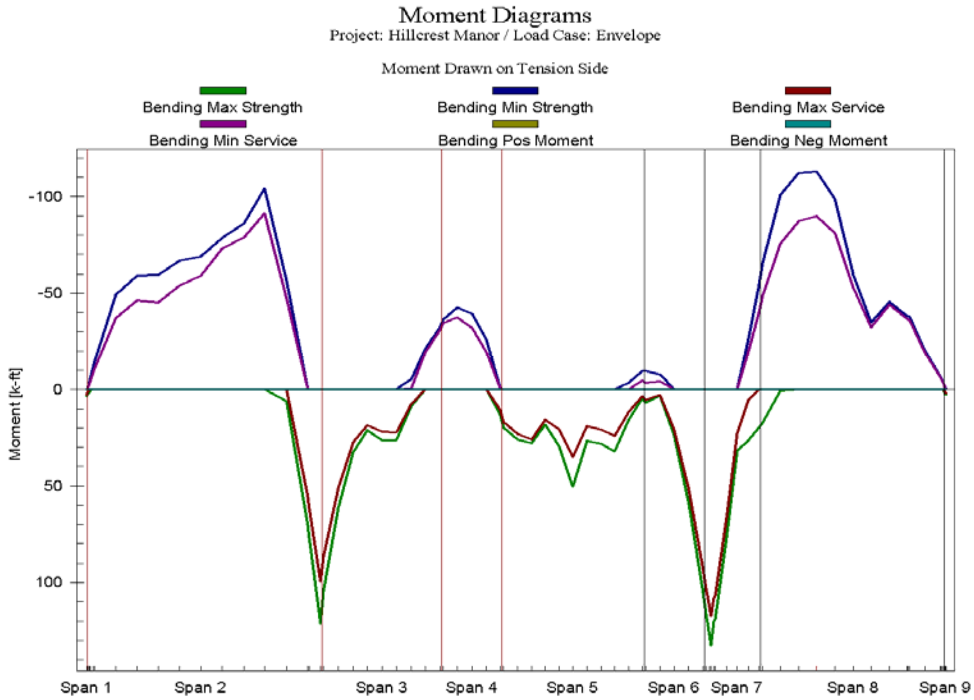


FIGURE 10.3-5 ENVELOPE OF DESIGN MOMENTS FROM ALL LOAD COMBINAITONS FOR DESIGN STRIP 7

11 - REINFORCEMENT

The envelope of rebar required in addition to the base reinforcement specified for the project in Section 6 is shown in Figs. 11-1 for the bottom bars. To illustrate the annotation used in reporting the reinforcement, a section of the plan is shown in enlarged view in Fig. 11-2.

The program also reports the reinforcement required in tabular form for each of the load combinations, as well as the envelope of all load combinations.

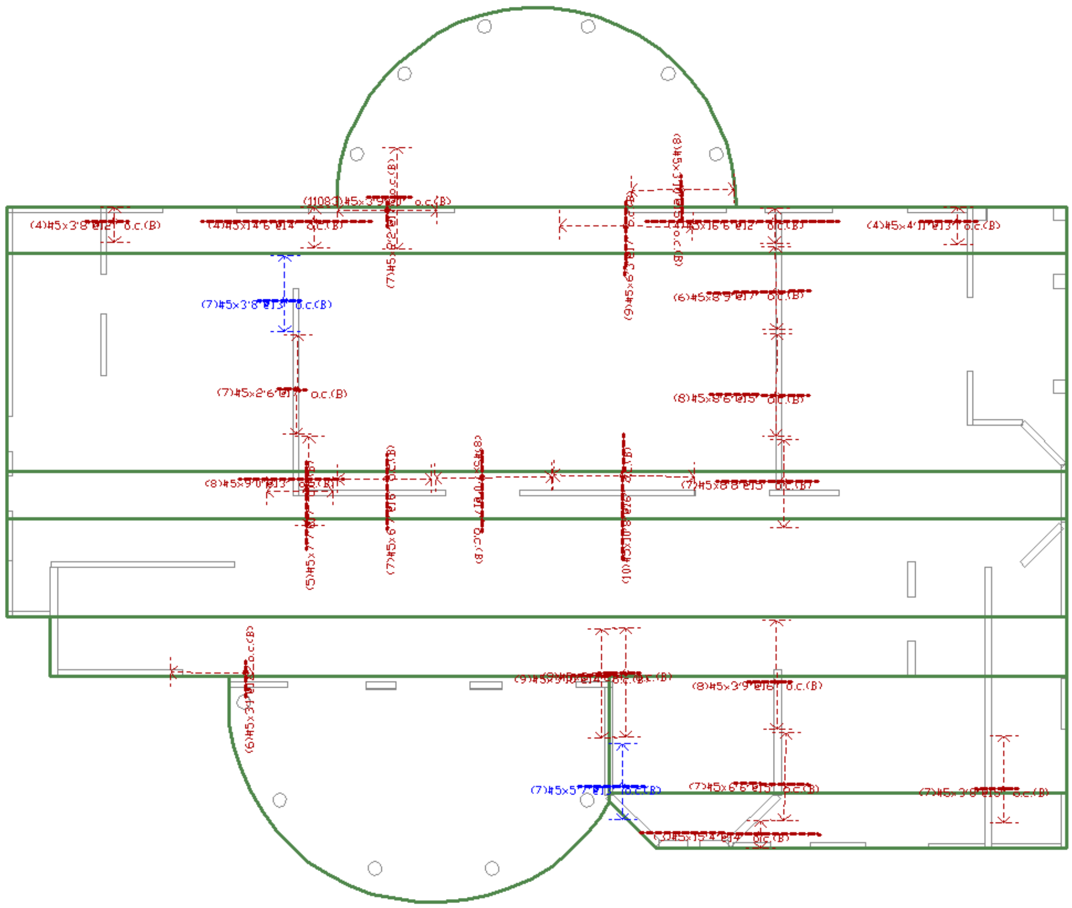


FIGURE 11-1 BOTTOM REBAR IN ADDITION TO BASE REINFORCEMENT

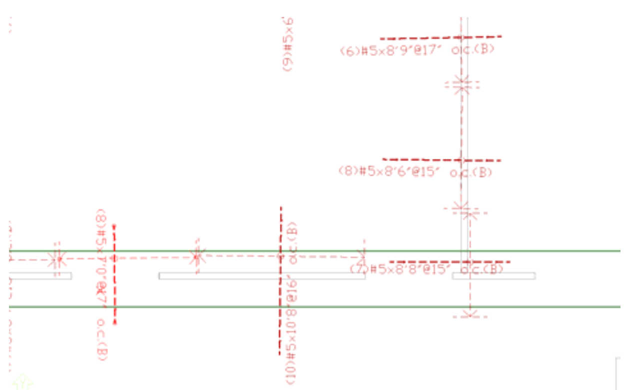


FIGURE 11-2 ENLARGED VIEW OF A SLAB REGION SHOWING THE REQUIRED BOTTOM REBAR

Top bar is required at one location only as illustrated in Fig. 11-3. The base reinforcement specified covers the requirements for other locations.

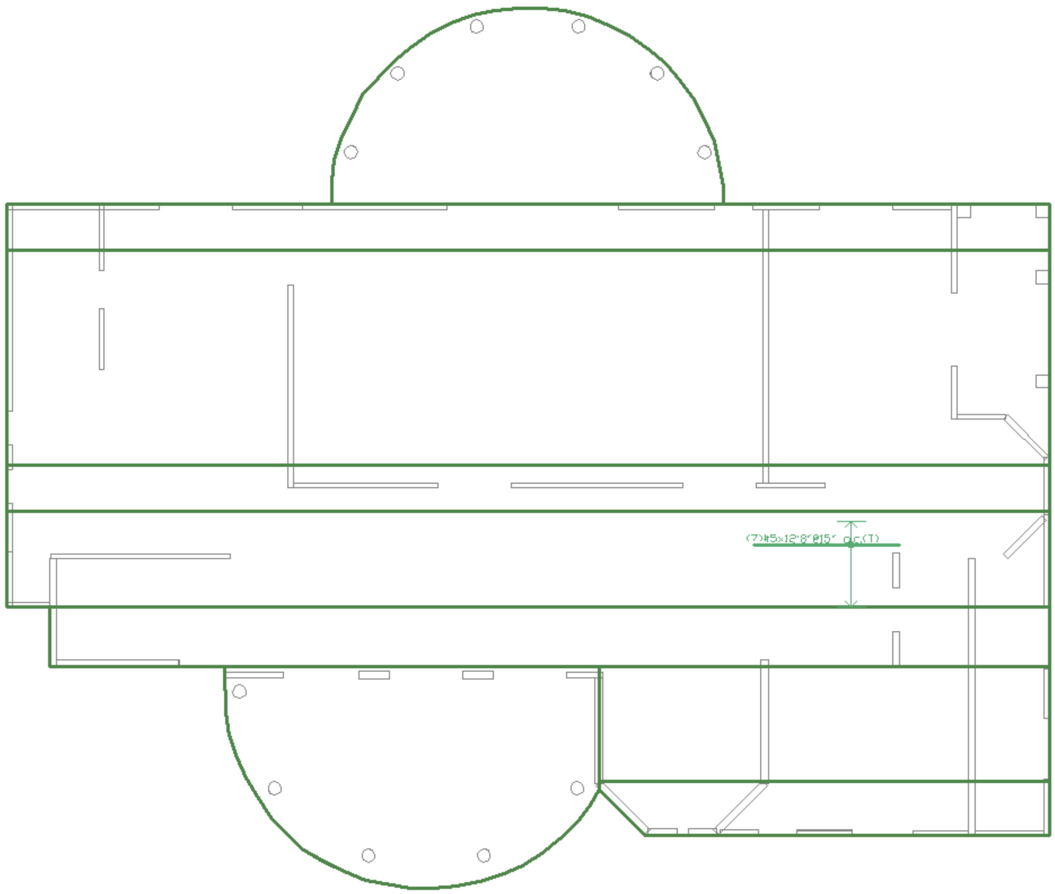


FIGURE 11-3 TOP REBAR IN ADDITION TO BASE REINFORCEMENT

12 - PUNCHING SHEAR

Punching shear is performed for columns and walls with an aspect ratio not exceeding 4. The outcome of stress check is shown graphically (Fig. 12-1). The value of stress check for each column is reported on the plan (Fig. 12-1) as well as in tables. Where required, the program provides punching shear reinforcement.

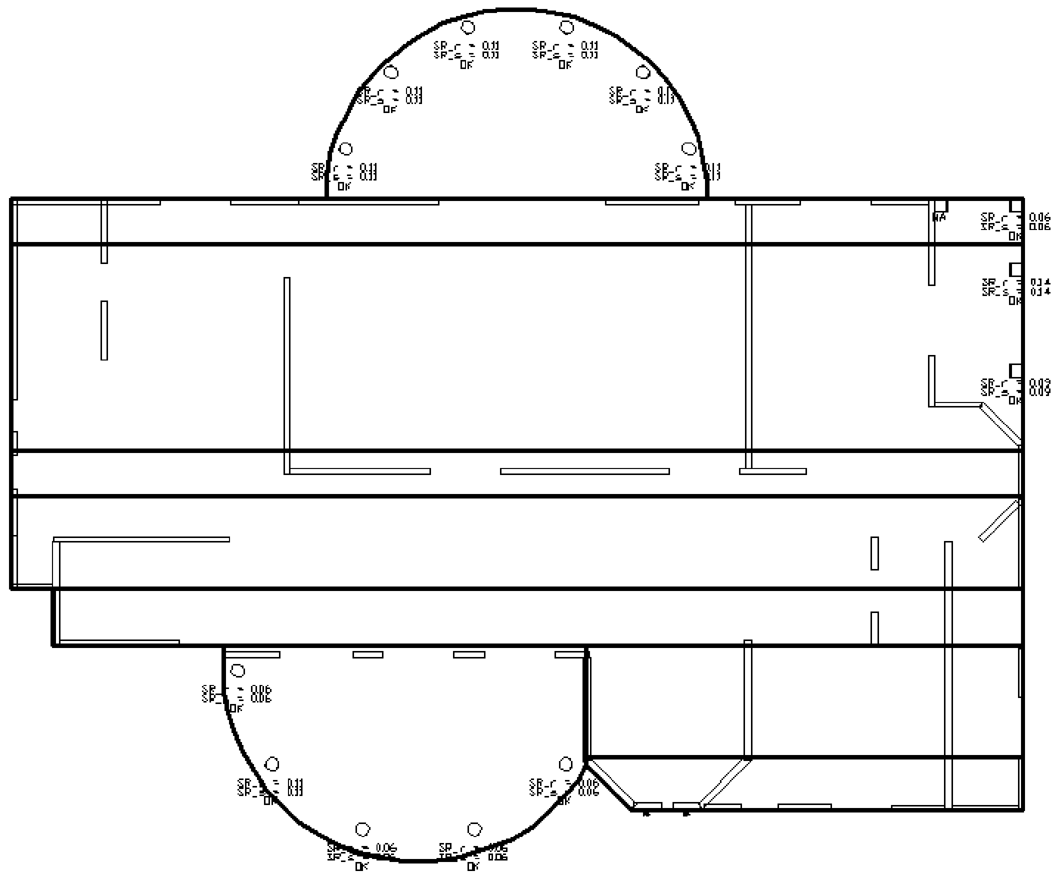


FIGURE 12-1 RESULTS OF PUNCHING SHEAR CHECK FOR COLUMNS