Analysis & Design of The Gateway Building

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INTRODUCTION

- **The Gateway Building is a multi-functional structure located in Ramallah, Al-Irsal ST.**

- **Number of stories is 13, of which are:**
    - 4 basement floors.
    - 2 floors serving as store spaces.
    - 5 floors serving as office spaces.
    - 2 uppermost floors serving as restaurants.

- **Total area of the building is 14,000 Sq. meters.**

INTRODUCTION

- All floors have a height of 3 meters each. Total height of the building is 42 meters.

INTRODUCTION

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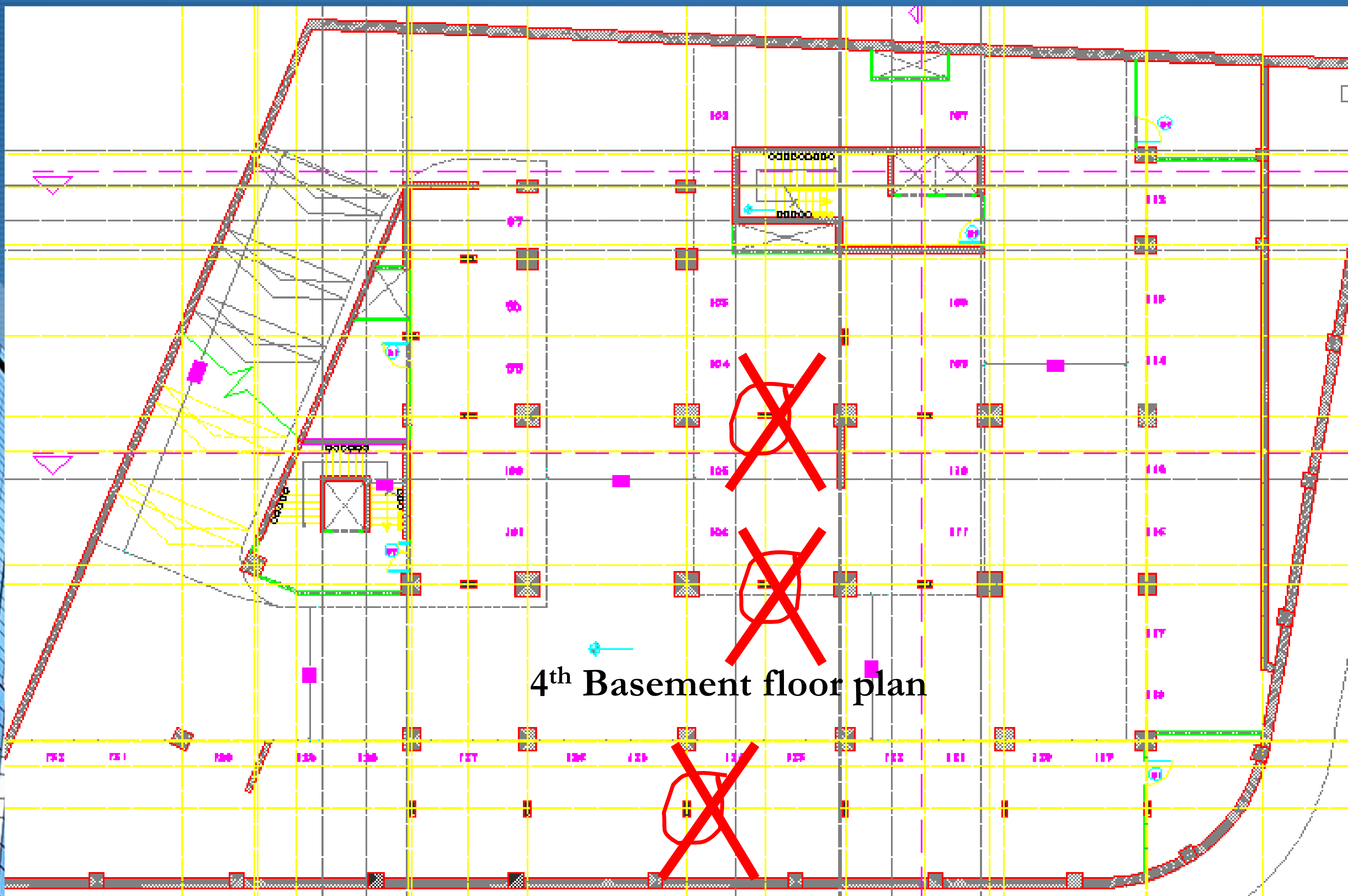
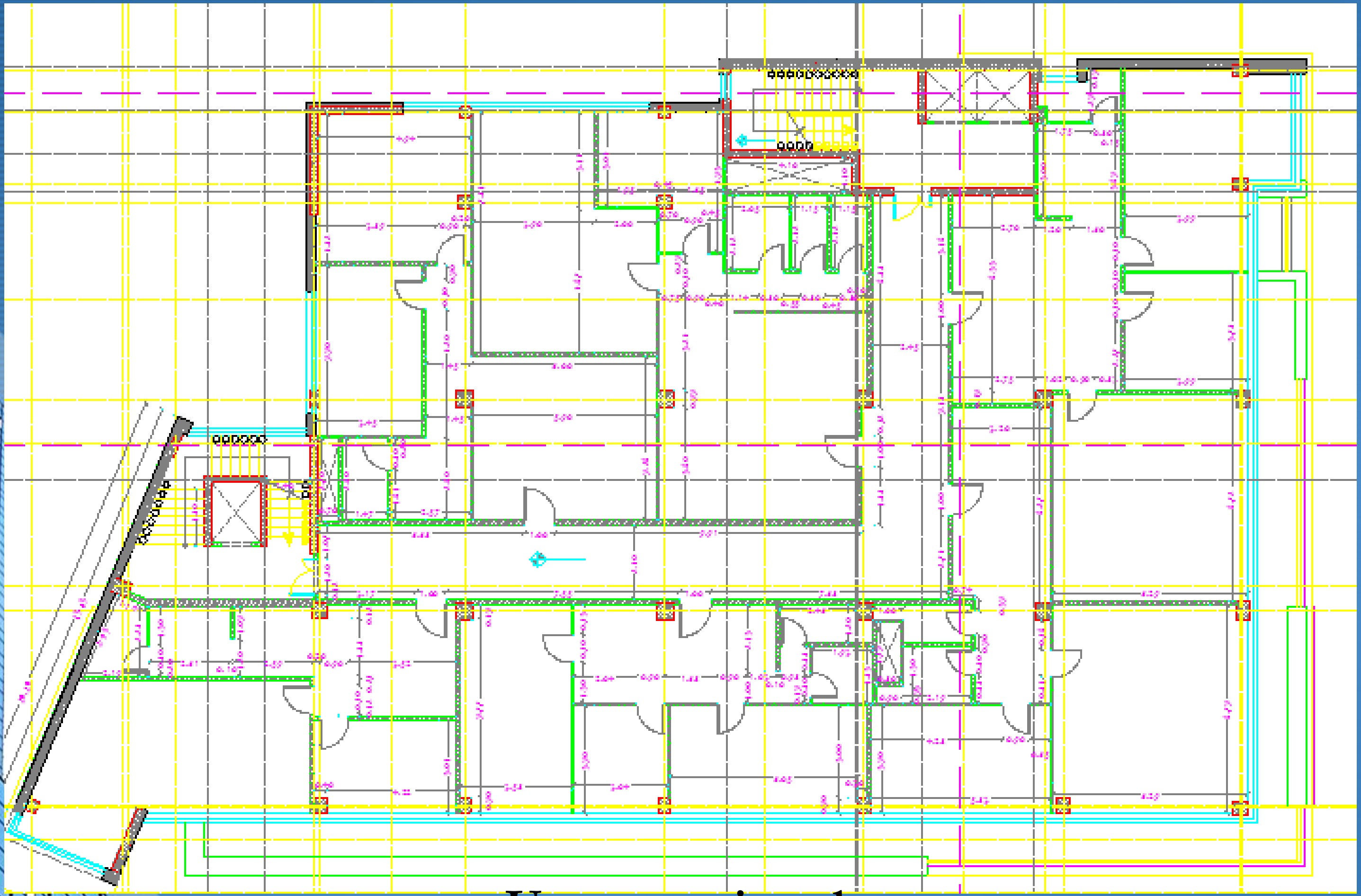


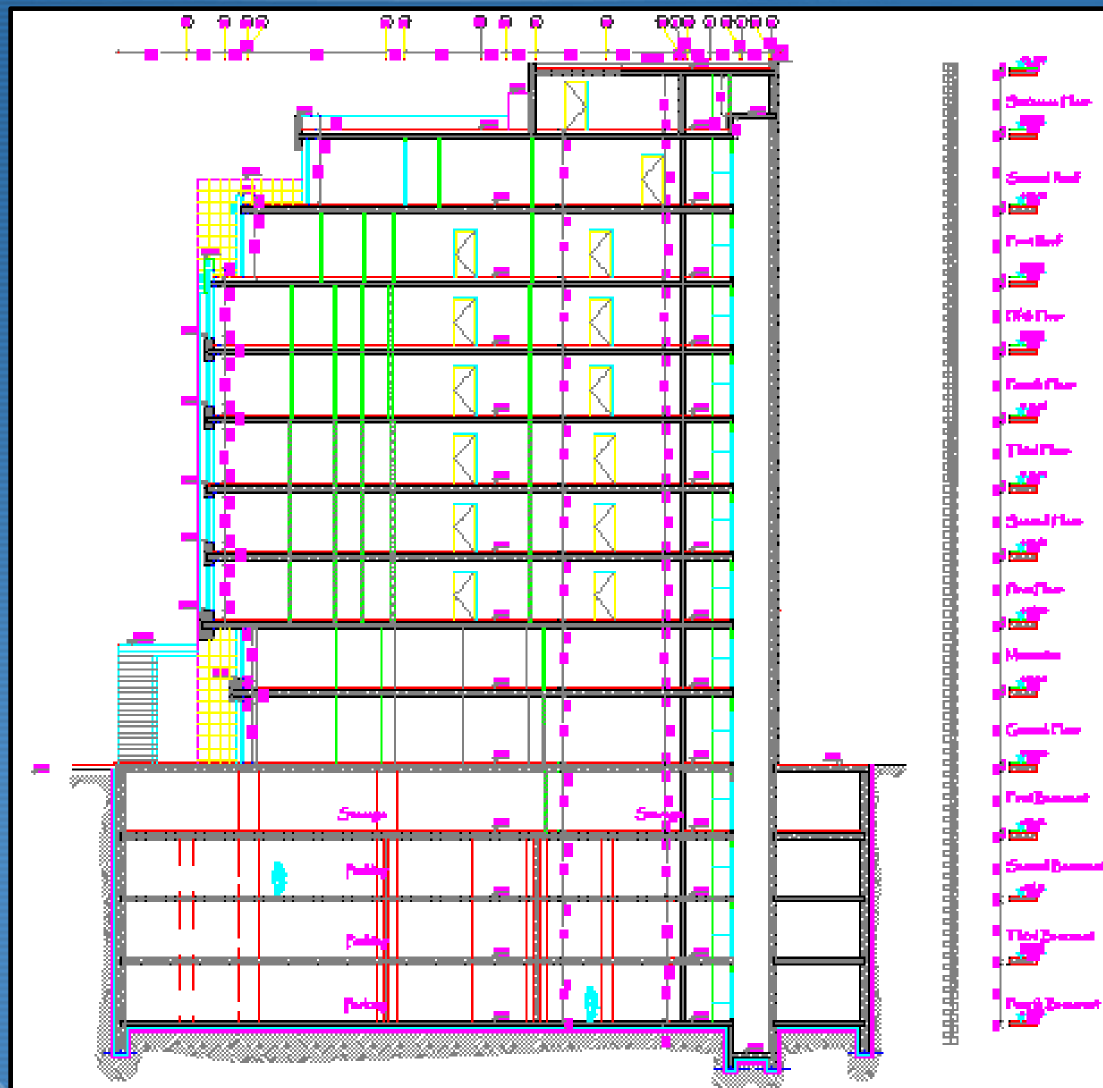
4[th] Basement floor plan

INTRODUCTION



Upper stories plan

INTRODUCTION



PURPOSE

- The purpose of this project is to provide analysis and design for both static and dynamic loads.
- Static loads investigated include self-weight of the building, live loads and lateral backfill pressure.
- Dynamic loads considered result from potential earthquakes.

PURPOSE

- The goal is to use reinforced concrete to resist forces and fulfill both safety and economy.
- As per dynamic loads, the goal of design is to prevent any threat to life. Plastic deformations may occur but will not affect life safety.

PURPOSE

- Analysis and design are carried out using ETABS 2013 and SAFE V12.
- ETABS 2013 is used to create the numerical model and provide reinforced concrete design for columns and walls.
- SAFE V12. is used for designing slabs and the foundations.

STRUCTURAL TOPOLOGY

- Codes used in Analysis and design

Code	Use
ASCE /SEI 7-10	Minimum design loads, minimum section requirements and load combinations.
ACI Code 318-11	Frames and shear wall section design and rebar.
ACI Code 318-08	Slab and mat foundation design using SAFE v12
UBC 97	Earthquake analysis

Structural Topology

- Materials Used:

Concrete			
Usage	Strength f'_c (MPa)	Unit Weight (kN/m^3)	Modulus of Elasticity (MPa)
Foundation	35	23.54	27806
Columns	35	23.54	27806
Shear Walls	28	23.54	24870
Slabs	28	23.54	24870

Rebar Steel				
Usage	Min. Yield Strength (MPa)	Min. Tensile Strength (MPa)	Unit Weight (kN/m^3)	Modulus of Elasticity (MPa)
Foundation	413	621	77	200E+3
Columns	413	621	77	200E+3
Shear Walls	413	621	77	200E+3
Slabs	413	621	77	200E+3

All materials are linear, elastic and isotropic

Structural Topology

- The design loads are: dead, superimposed, lateral earth pressure, snow and live loads.
- Dead load is the self weight of structural elements.
- Snow load is calculated assuming a potential snow height of 70cm with snow density of 300 kg/cubic meters.
- Superimposed, lateral earth pressure and live loads comply with the ASCE code. Each floor carries a load according to its function.

Structural Topology

- For lateral earth force, the backfill soil is silty gravels with a design lateral load value of 5.50 kN/m2 per one meter of depth. ***(ASCE Table 3.2-1)***

Basement Floor	Depth below grade (m)	Lateral earth pressure (kN/m^2)
4th basement	12	66
3rd basement	9	49.5
2nd basement	6	33
1st basement	3	16.5

Structural Topology-Loads

Floor	Function	Live Load (kN/m^2)	Dead Load (kN/m^2)	Superimposed Dead Load (kN/m^2)	Snow Load (kN/m^2
4th basement	Parking	2.5	Self weight	0	0
3rd basement	Parking	2.5	Self weight	0	0
2nd basement	Parking	2.5	Self weight	0	0
1st basement	Parking	2.5	Self weight	0	0
Ground Floor	Store spaces	3.6	Self weight	2	0
Mezzanine Floor	Store spaces	3.6	Self weight	2	0
1st floor	Office spaces	2.4	Self weight	2	0
2nd floor	Office spaces	2.4	Self weight	2	0
3rd floor	Office spaces	2.4	Self weight	2	0
4th floor	Office spaces	2.4	Self weight	2	0
5th floor	Office spaces	2.4	Self weight	2	0
1st roof floor	Restaurants	4.8	Self weight	2	0
2nd roof floor	Restaurants	4.8	Self weight	0	2
Staircase floor	Staircase	1	Self weight	0	2

Structural Topology

- Load Combinations Used:

Comb1: U= 1.4D
Comb2: U=1.2D + 1.6L
Comb3: U=1.2D + 1.6L + 0.5S
Comb4: U=1.2D+1.6L+ 0.5S+1.6H
Comb5: U=Envelope (Comb1, Comb2, Comb3, Comb4)

Comb5 is used for design

Structural Topology

- Soil Conditions:

The Structure is built on rock that has a bearing capacity of 250 kN/m2. Soil is treated at linear and elastic material.

Numerical Model

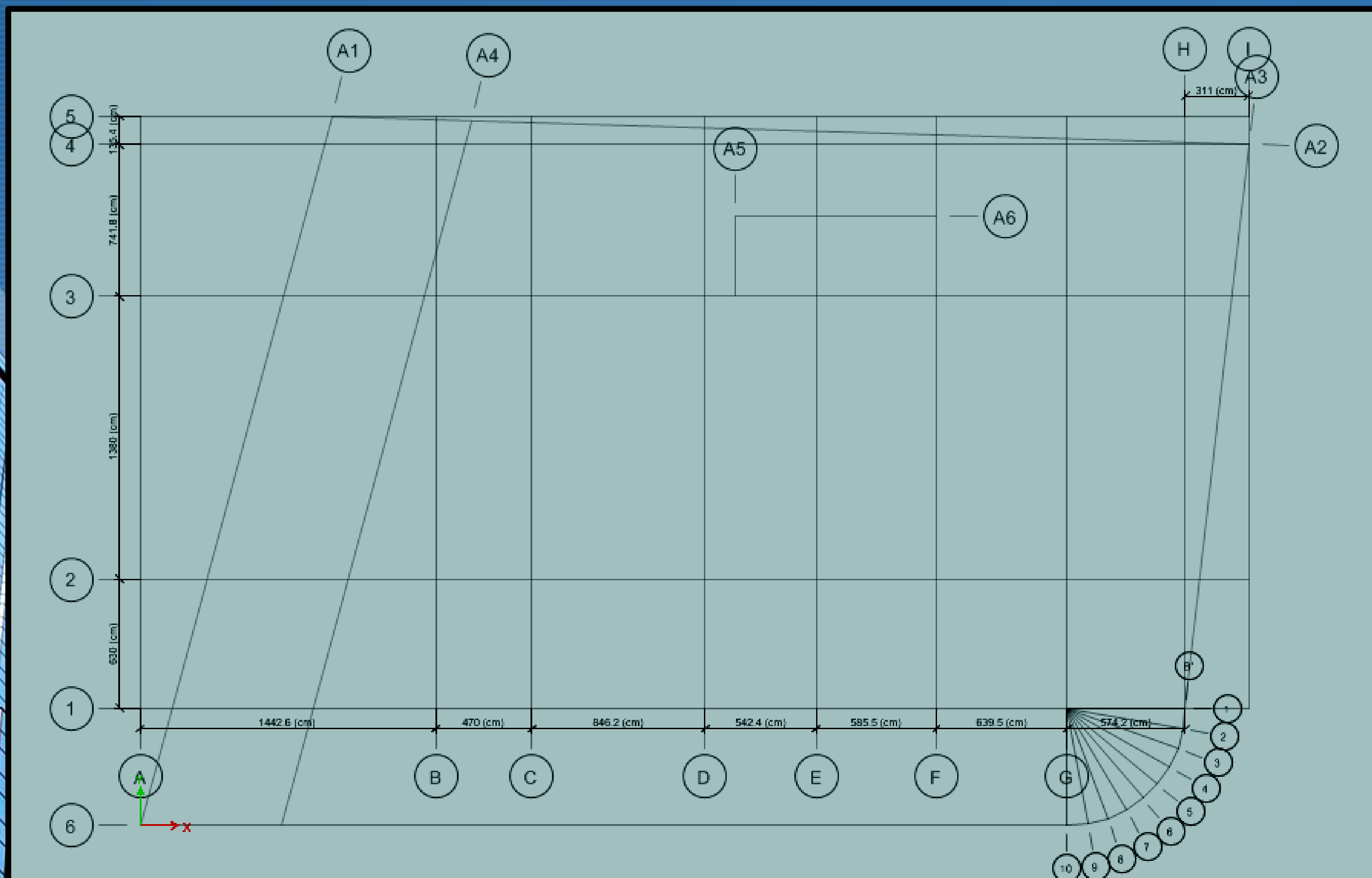
- ETABS 2013 is used to create the building model. This version is the latest one that CSI Berkley has produced.

- The model is three-dimensional and finite-element based.

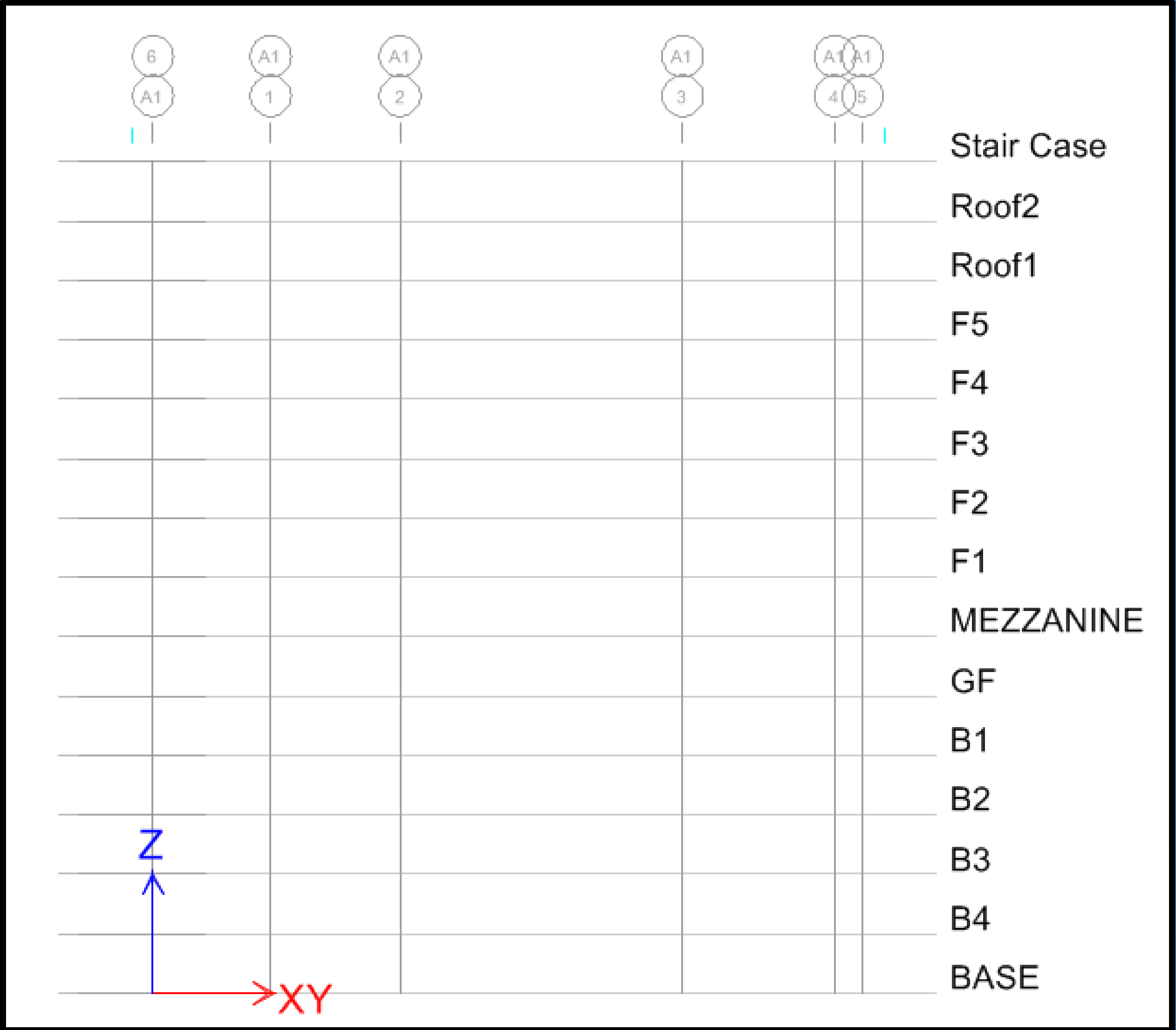
Numerical Model: Geometry

- Model is created in partial conformity with the original architectural plans.
- The main challenge is eliminating some columns that were deemed superfluous, thus having longer span lengths.
- Metric SI units are used in the model.
- Both Cartesian and cylindrical grid-systems are used in the model.

Numerical Model: Geometry



Numerical Model: Geometry



Numerical Model: Geometry

Floor Name	Height (mm)	Elevation (mm)
Stair Case	3000	42000
Roof2	3000	39000
Roof1	3000	36000
F5	3000	33000
F4	3000	30000
F3	3000	27000
F2	3000	24000
F1	3000	21000
MEZZANINE	3000	18000
GF	3000	15000
B1	3000	12000
B2	3000	9000
B3	3000	6000
B4	3000	3000
Base	0	0

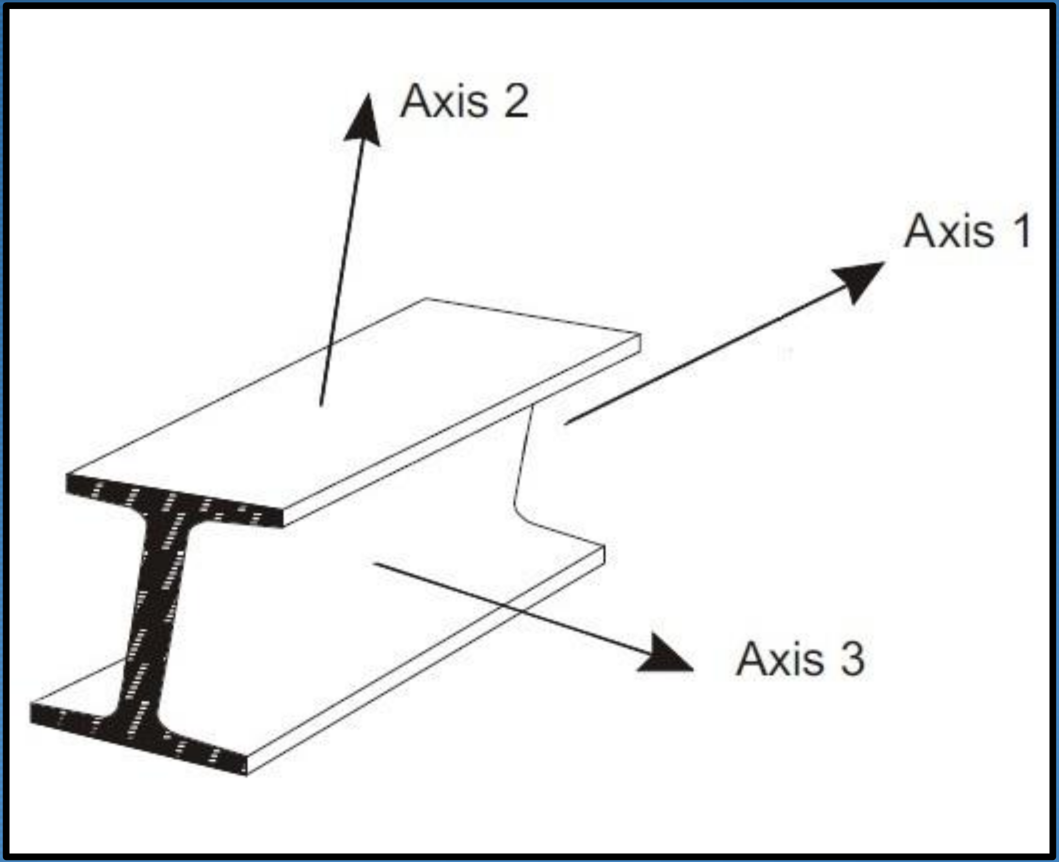
Numerical Model: Finite Elements

- Two types of elements are used in the model:
  - The frame element, used to model columns.
  - The shell element, used to model the mat foundation, walls and slabs.

Numerical Model: Finite Elements

- The frame element:
  - modeled as a straight line connecting two points.
  - Activates six degrees of freedom at both of its joints (three translational and three rotational)
  - Includes the effects of biaxial bending, torsion, axial deformation and biaxial shear deformations.

Numerical Model: Finite Elements



Frame element local axes

Numerical Model: Finite Elements

- Frame elements used in the model:

Frame element sections used in the model			
Section	Depth (mm)	Width (mm)	Material
C70x70	700	700	Concrete_35MPa
C40X40	400	400	Concrete_35MPa

Columns at the base have pin connections, and also have rigid connections with the slabs

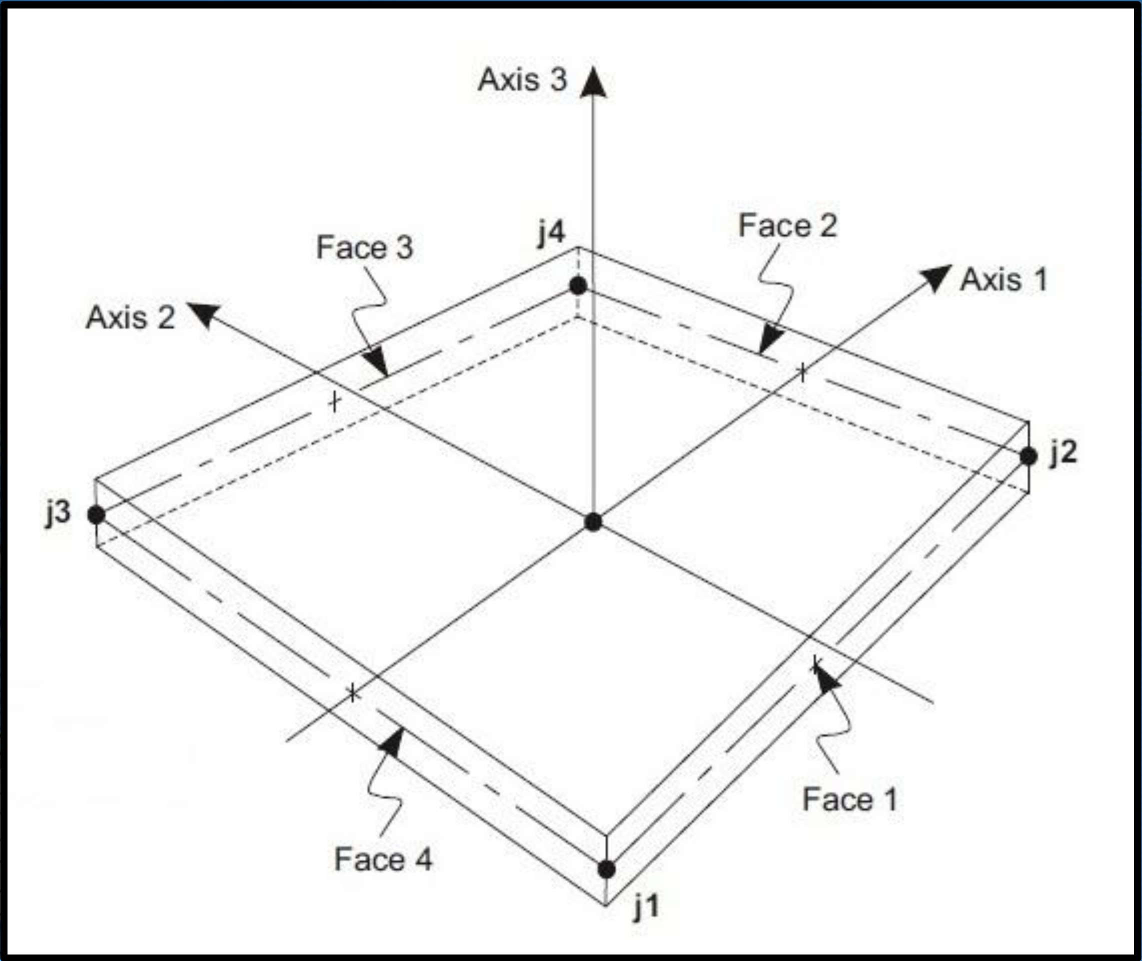
Numerical Model: Finite Elements

- Soil Springs:
  - Soil is modeled as springs with stiffness in the Z-direction. Stiffness in X and Y is zero.
  - **Spring stiffness= 40*safety factor*soil allowable pressure**
    = 40*2.5*250 = 25000 kN/cubic-meters
  - **Soil property is assigned to all shell elements that compose the mat foundation.**

Numerical Model: Finite Elements

- The Shell Element:
  - An area element that requires 3 nodes at least.
  - Most shell-elements in the model have 4 nodes, 3-noded elements were used at some locations.
  - Does not have to be planar.

Numerical Model: Finite Elements



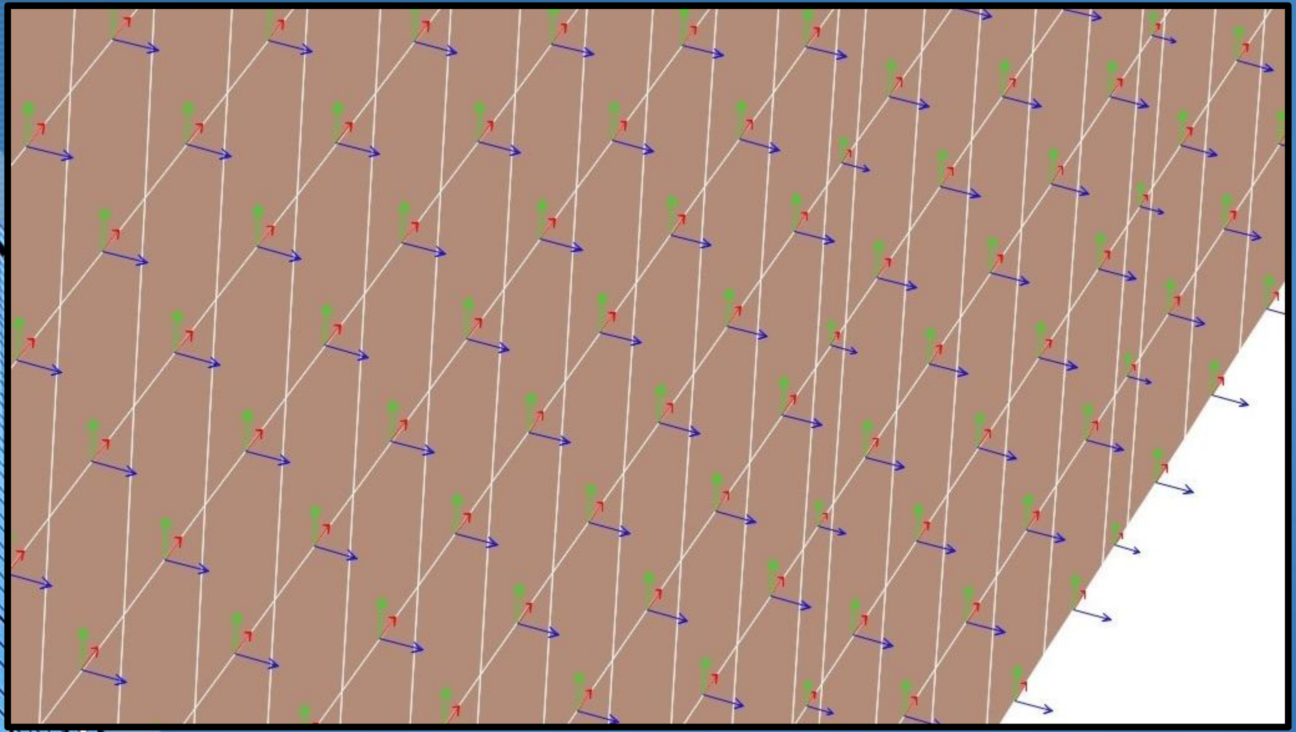
Each node has 6 DOF'S

Combines both in-plane and out-of-plane behavior

Shell-elements used are thin; means we neglect shear deformations

Numerical Model: Finite Elements

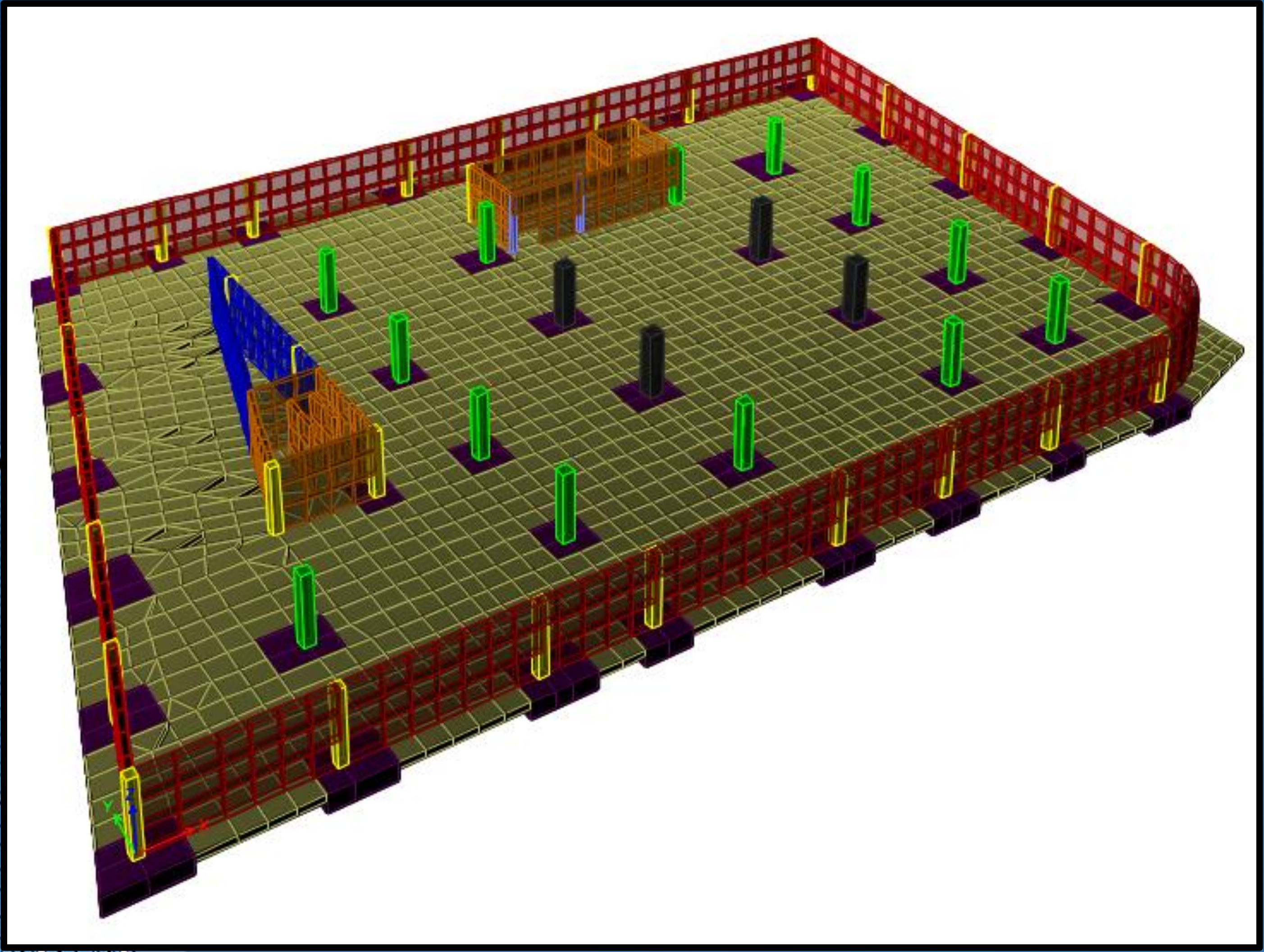
- Local axes of shell-elements were made uniform, this facilitates load assignment and retrieving analysis results (forces and stresses)



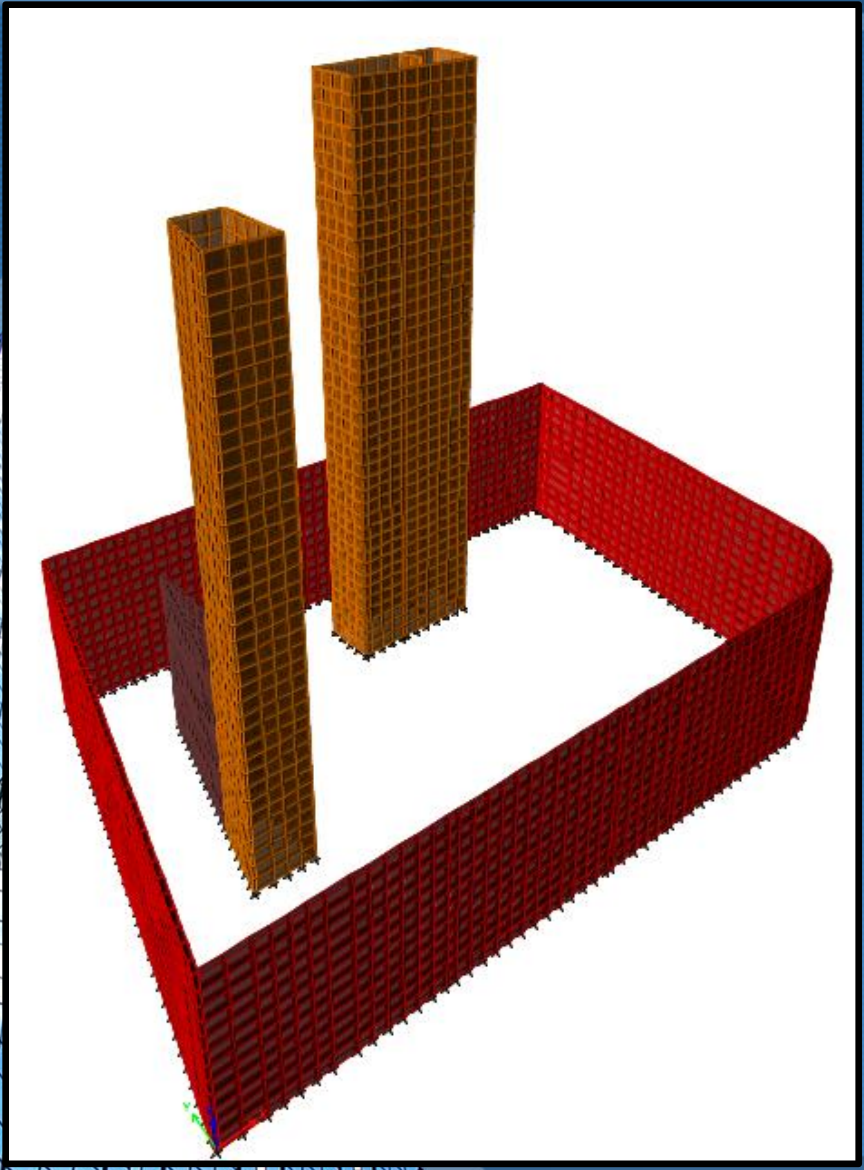
Numerical Model: Finite Elements

- The Mat Foundation:
  - Modeled using shell elements.
  - Has a thickness of 25cm with 60cm drop panels.
  - Concrete used has f’c= 35 Mpa.

Numerical Model: Finite Elements

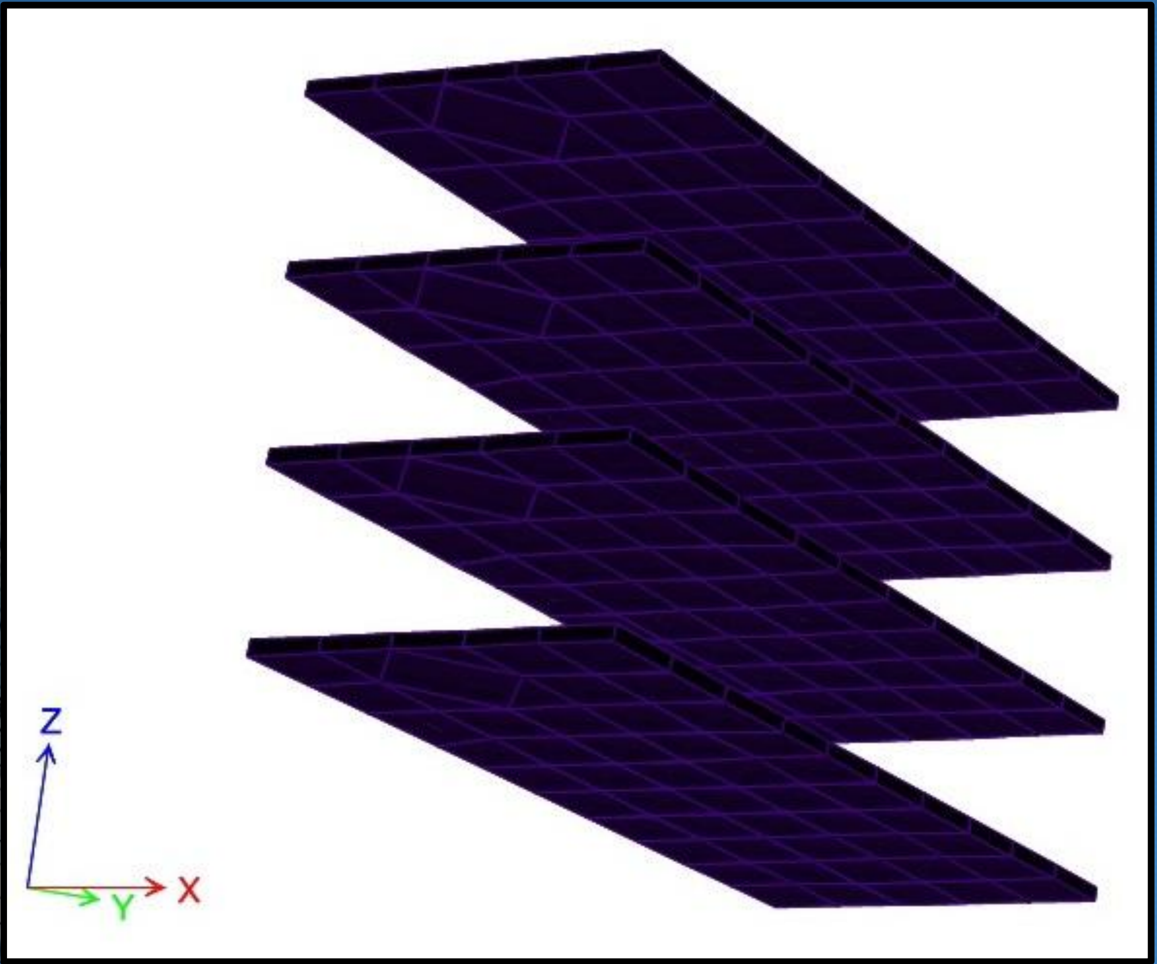


Numerical Model: Finite Elements



- Exterior walls: 30cm, resisting backfill forces.
- Interior walls: 20cm, acting as elevator cores and staircases.
- Are pin-connected at the bottom.
- Doors and windows are accounted for as openings.

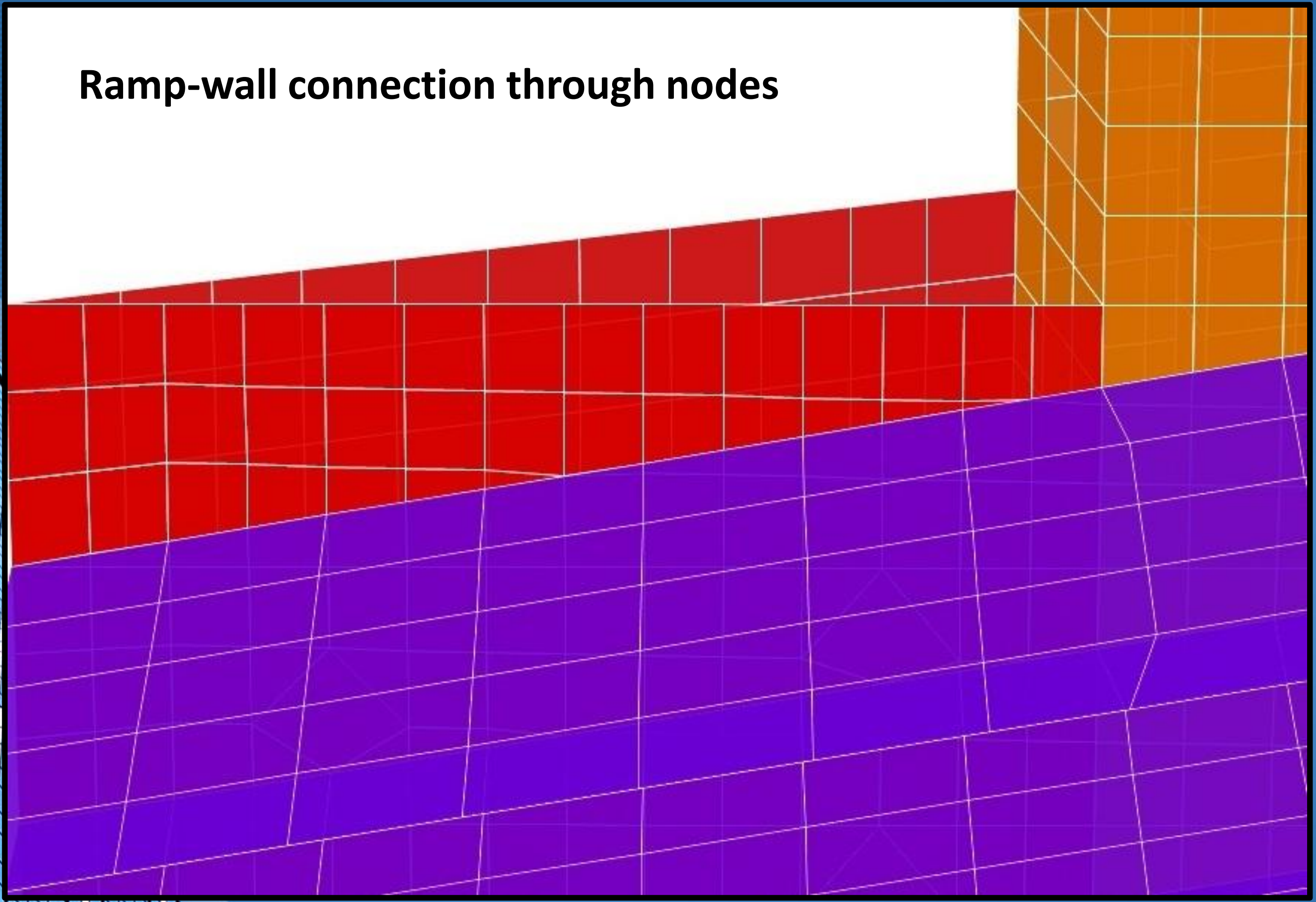
Numerical Model: Finite Elements



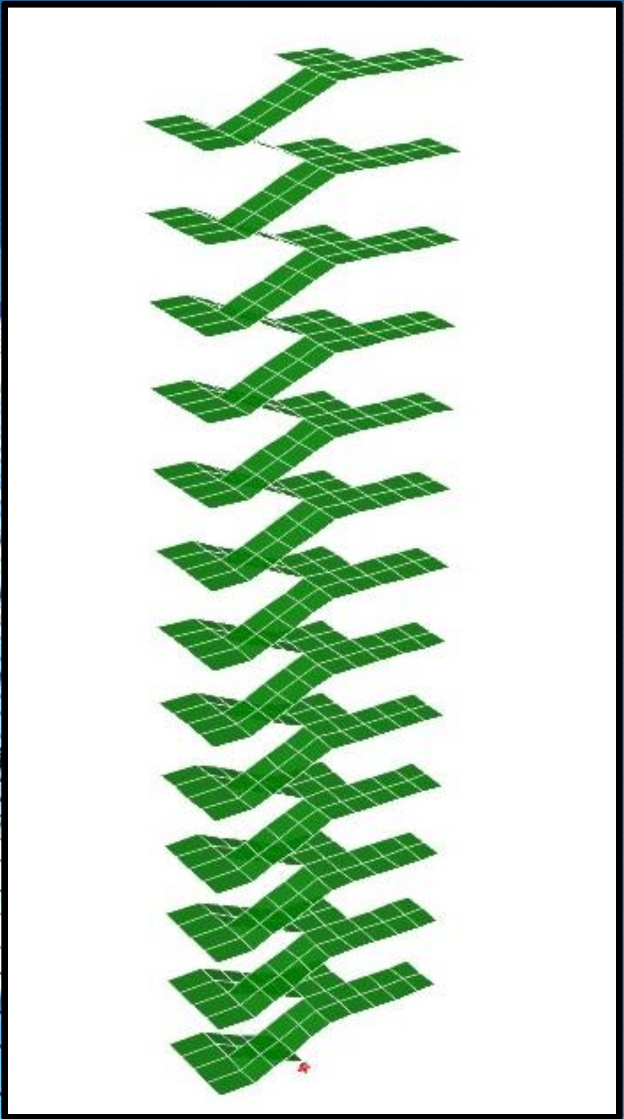
RAMPS

- Thickness of 25cm.
- Adequately connected with surrounding walls
- Modeled as shell elements.

Numerical Model: Finite Elements



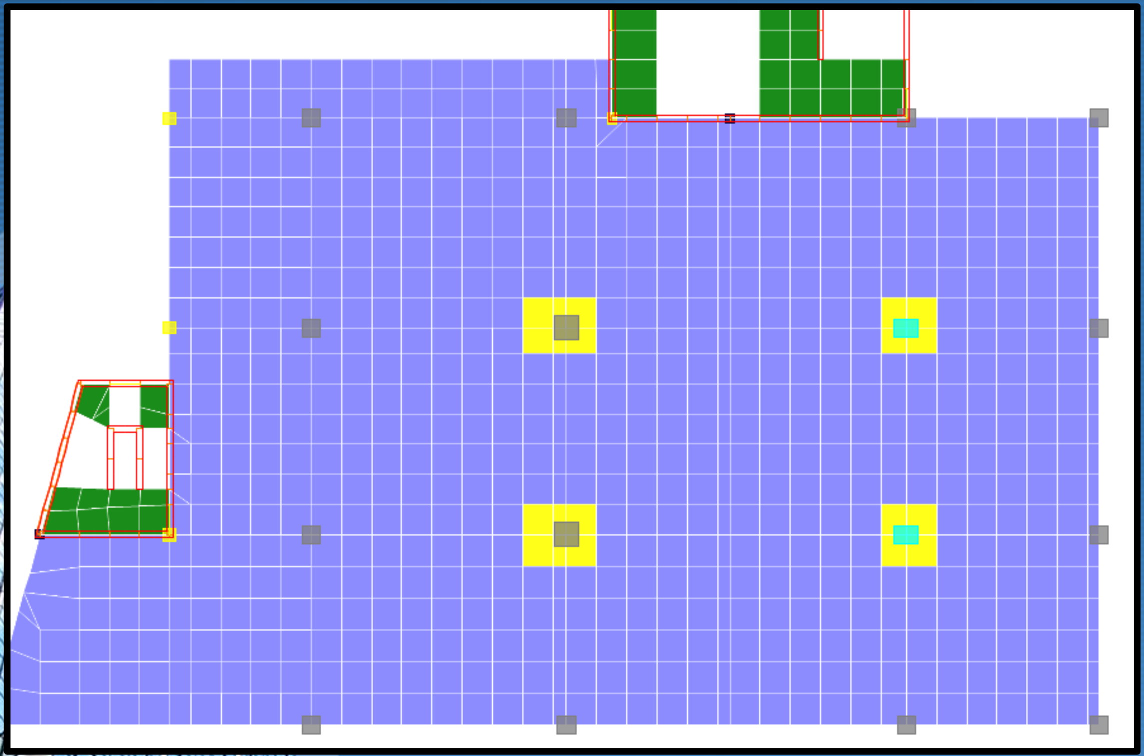
Numerical Model: Finite Elements



STAIRS

- Modeled as shell elements.
- Have thickness of 20cm.
- Adequately connected with slabs, and having no connection with surrounding walls.

Numerical Model: Finite Elements



SLABS

- Modeled as shell elements.
- Have thickness of 25cm.
- Adequately connected with walls.

Numerical Model: Procedure

- Bottom floor is created with high accuracy.
- Upper floors are not replicated until the single floor is checked against errors.
- Errors are checked using ETABS 2013 “Model Check Option” that checks area overlaps and nodes connection.
- A “RUN” is carried out for the single-story model, if there are errors, they had to be corrected, then upper stories were replicated.

Numerical Model: Procedure

- Types of errors encountered:
  - "Lost digits of accuracy", mostly to 6 or 7 digits. This was treated by carefully connecting elements through nodes and by avoiding ill-conditioned angles.
  - "Instability", means that ETABS cannot solve matrices due to singular matrix formation. This means the whole structure or some elements are unstable.

Numerical Model: Procedure

- Using the law of equilibrium, we applied 100kN test point load at some location in the model in the 3 directions.

- ETABS output for the base reactions:

Load Case/Combo	FX kN	FY kN	FZ kN	
TEST	-100	-100	100	6

Numerical Model: Load Assignment

- All slabs having the same load values are selected together, then load is assigned as an area uniform load in the gravity direction, except for basement walls, were backfill load is applied in the negative local-3-direction.

Preliminary Results: Punching shear

- Punching shear is a concern, so it was checked in the preliminary stage of design.
- Punching shear is checked using SAFE V12.
- SAFE uses the following equation:

$$v_U = \frac{Vu}{bod} + \frac{\gamma vx\{Mux - Vu(y3 - y1)\}\big(Iyy(y4 - y3) - Ixy(x4 - x3)\big)}{IxxIyy - (Ixy)^2} - \frac{\gamma vy\{Muy - Vu(x3 - x1)\}\big(Ixx(x4 - x3) - Ixy(y4 - y3)\big)}{IxxIyy - Ixy}$$

Preliminary Results: Punching shear

- Concrete shear capacity is checked against ultimate shear stress.

- $V_c = 1/3 * \sqrt{f'_c} * b_\circ * d$, where $b_\circ$ is effective perimeter of the section.

- Punching shear ratio is V_u / V_c.

- This ratio should be less than one, otherwise, drop panels should be added.

Preliminary Results: Punching shear

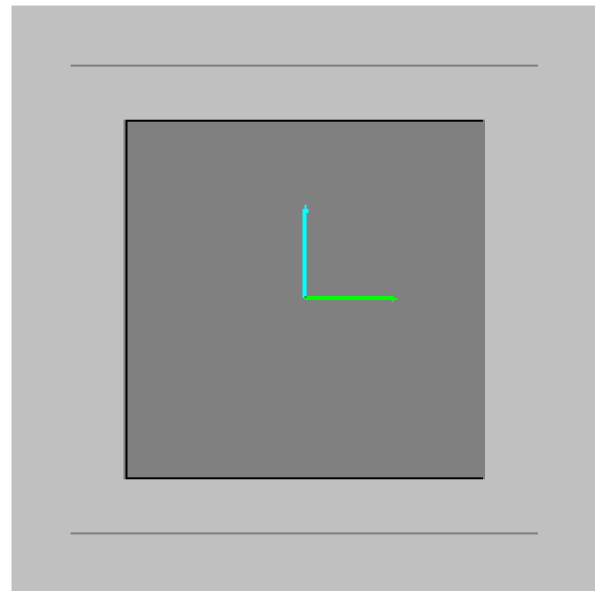
ACI 318-08 Punching Shear Check & Design

Geometric Properties

Combination = Comb4
Point Label = 2092
Column Shape = Rectangular
Column Location = Interior
Global X-Coordinate = 27.588 m
Global Y-Coordinate = 25.842 m

Column Punching Check

Avg. Eff. Slab Thickness = 217 mm
Eff. Punching Perimeter = 3668 mm
Cover = 33 mm
Conc. Comp. Strength = 28 N/mm2
Reinforcement Ratio = 0.0000
Section Inertia I22 = 1.131E+11 mm4
Section Inertia I33 = 1.131E+11 mm4
Section Inertia I23 = 0 mm4
Shear Force = 732.716 kN
Moment Mu2 = -1.1582 kN-m
Moment Mu3= 43.6902 kN-m
Max Design Shear Stress = 1.10234 N/mm2
Conc. Shear Stress Capacity = 1.318135 N/mm2
Punching Shear Ratio = 0.84



Column Punching Perimeter

Preliminary Results: Punching shear

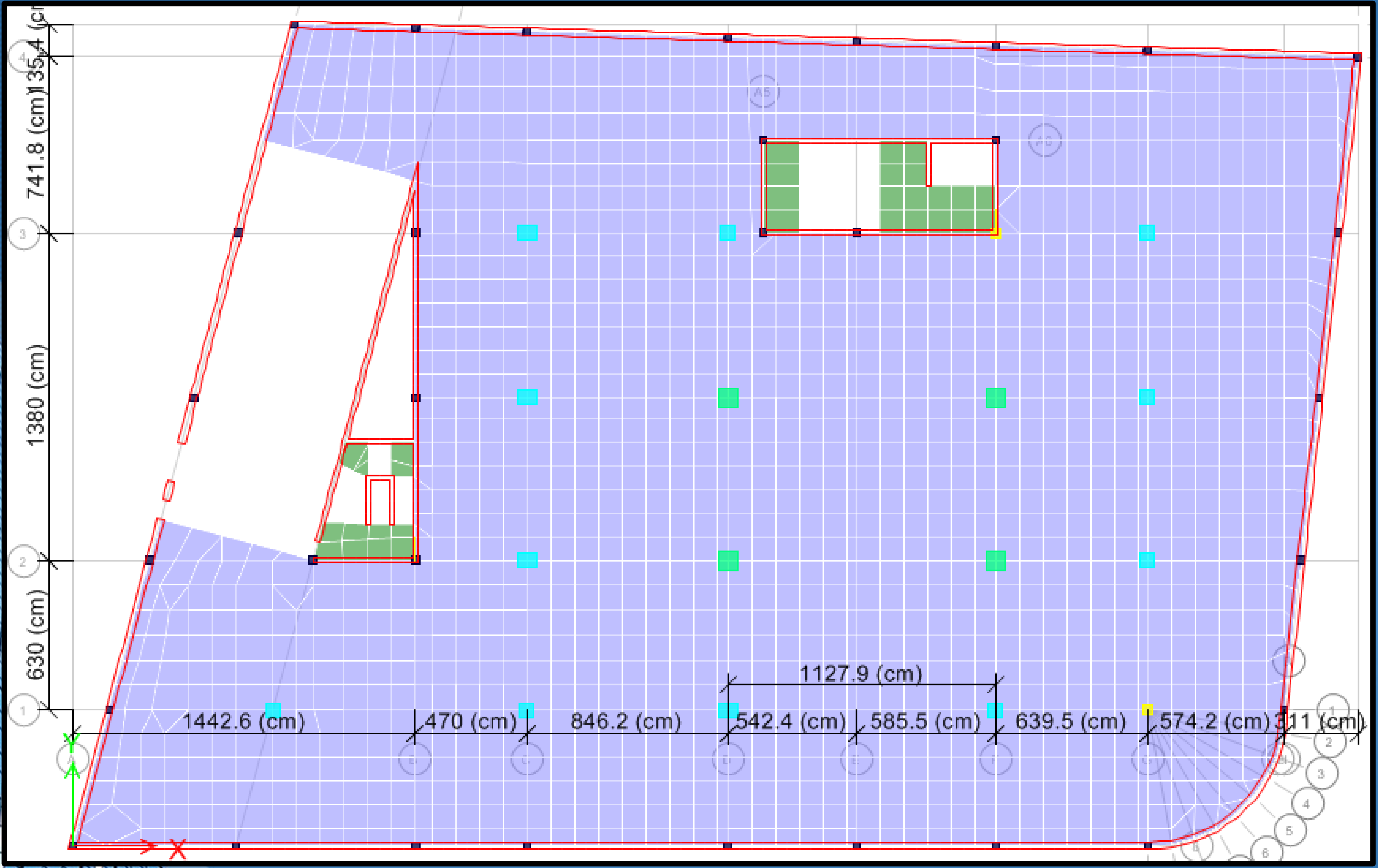
- Preliminary design of slabs required the use of drop panels with 40cm thickness for all slabs except the basements. This is necessary for resisting punching shear.

Preliminary Results: Deflection

- Maximum slab deflection is found using SAFE. It has found that maximum deflection occur at the longest span of length 11.3 meters.

Floor	Case	Max. deflection, U_z (mm)	Location		Critical Span length (mm)	Allowable Deflection (mm)	Status
			X	Y			
Roof 1	Comb4	22.99	33.012	15.042	11300	23.5	OK
GF	Comb4	21.59	33.012	15.042	11300	23.5	OK
B4	Comb4	22.54	33.012	15.042	11300	23.5	OK
F1	Comb4	18.57	33.012	15.042	11330	23.5	OK

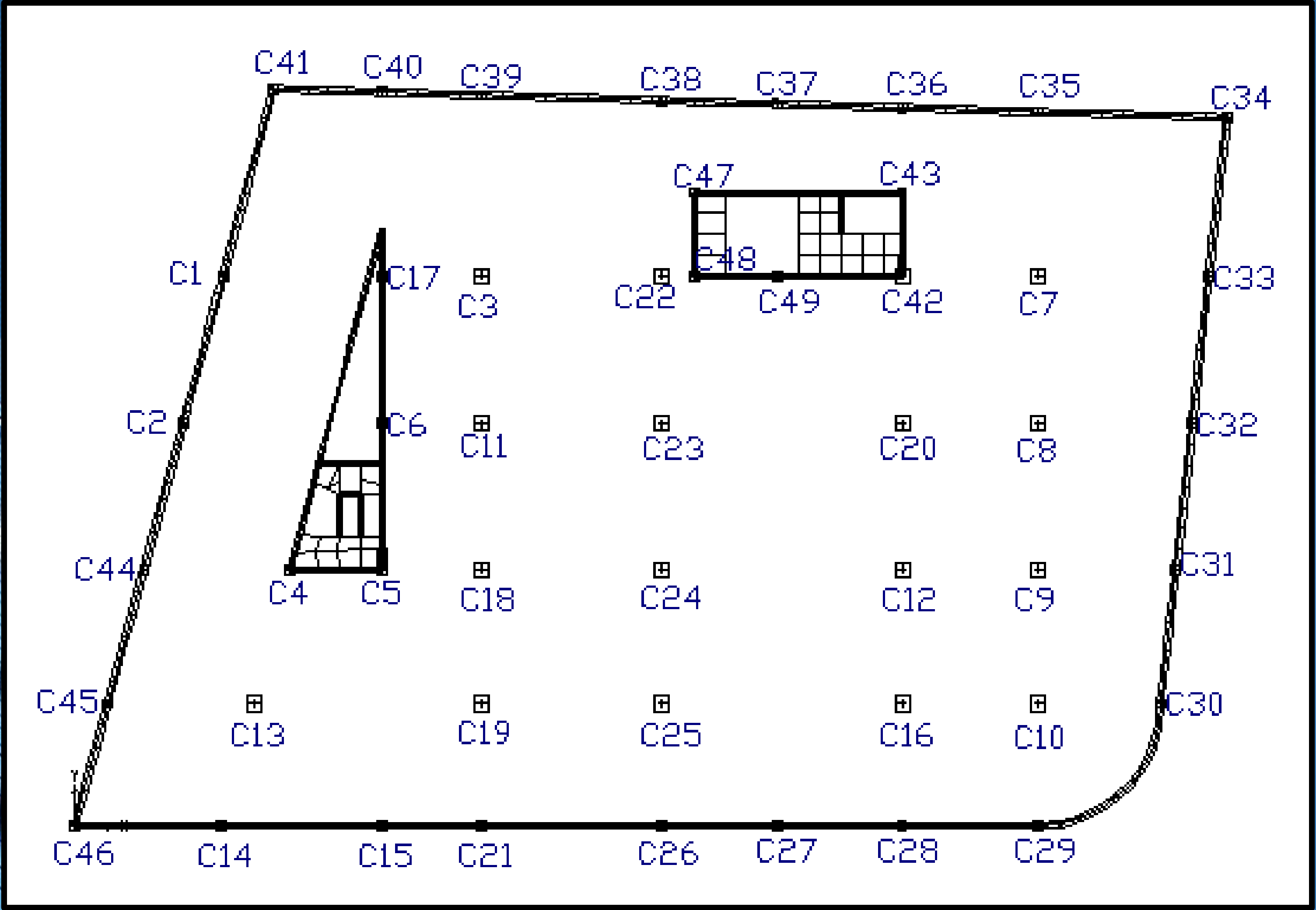
Preliminary Results: Deflection



Static Design

- Column Design:
  - Multiple concrete sections were added to ETABS. Largest is 80x80cm and smallest is 30x30cm.
  - The selected concrete frame sections were added to an “auto-select” list.
  - The main goal of this is:
    - Optimization: selecting minimum dimensions to resist loads.
    - Uniformity: keeping number of section to a minimum to ease the construction process.

Static Design



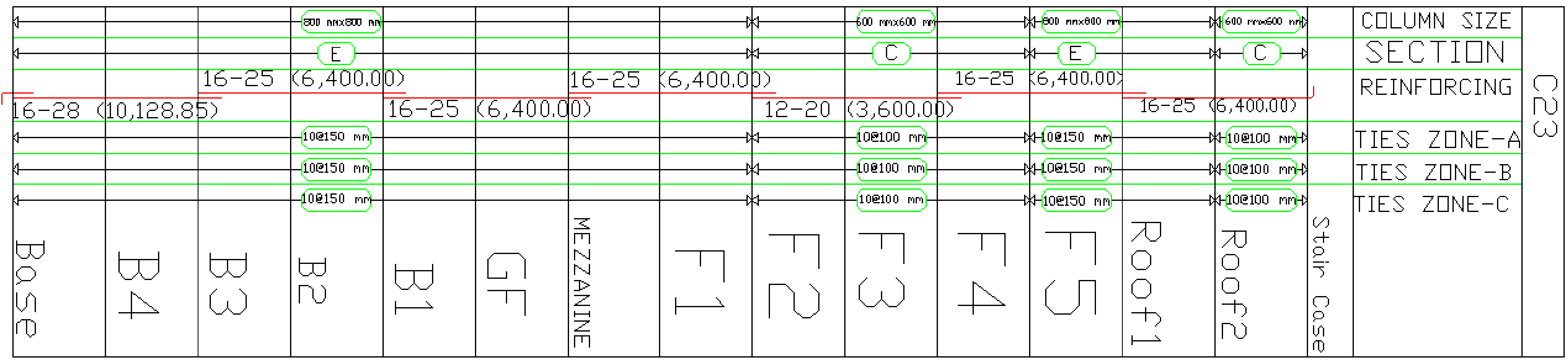
Static Design

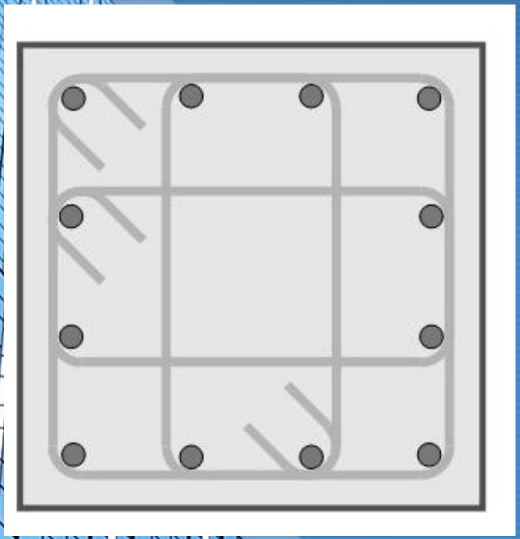
Column Label	Comb	Station m	P kN	V2 kN	V3 kN	T kN.m	M2 kN.m	M3 kN.m
C22	Comb5	0	-4405	-402	-142	1.69	-408	-1094
		3	-4342	-402	-142	1.69	31	112
C23	Comb5	0	-9175	-228	98	1.33	202	-548
		3	-9112	-228	98	1.33	-54	189
C13	Comb5	0	-2690	-20	-13.	-0.4	-9.15	-28
		3	-2666	-20	-13	-0.4	46.77	40
C48	Comb5	0	-395	2	-11	0.76	-13	10.6
		3	-228	-4.6	25.8	-0.69	-12.9	5.7

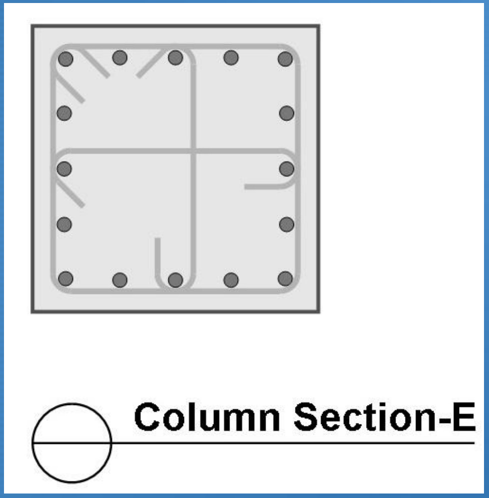
Forces in some columns in the 4th basement

equation $\Phi\ Pn_{(max)} = 0.80\phi\ [0.85f'_c\ (A_g - A_{st}) + f_y A_{st}]$, where $\Phi=0.65$, $f'_c=35$ MPa and A_{st} assumed as 3%, a section of 550x550mm would we adequate for resisting the axial force on C23 column, but the design section is larger due to high biaxial moment effects acting on the section.

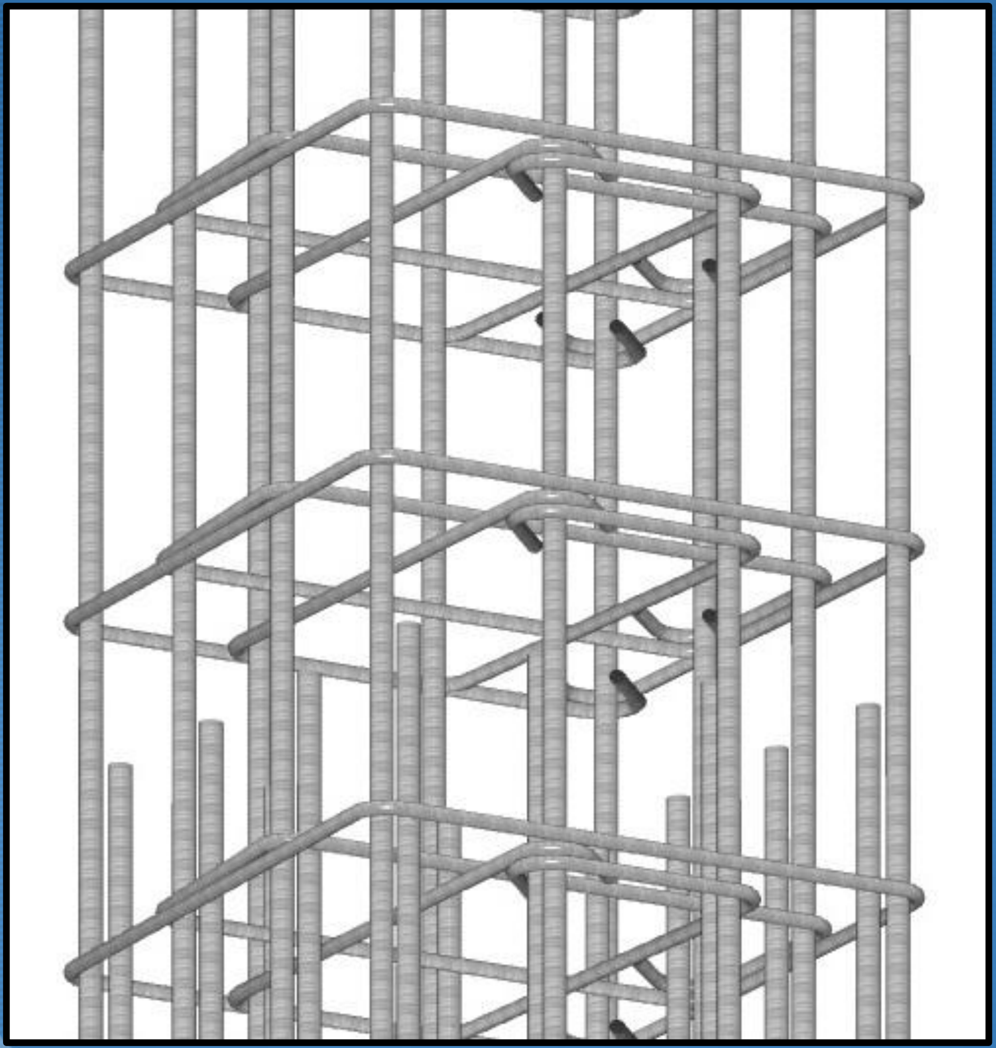
Static Design







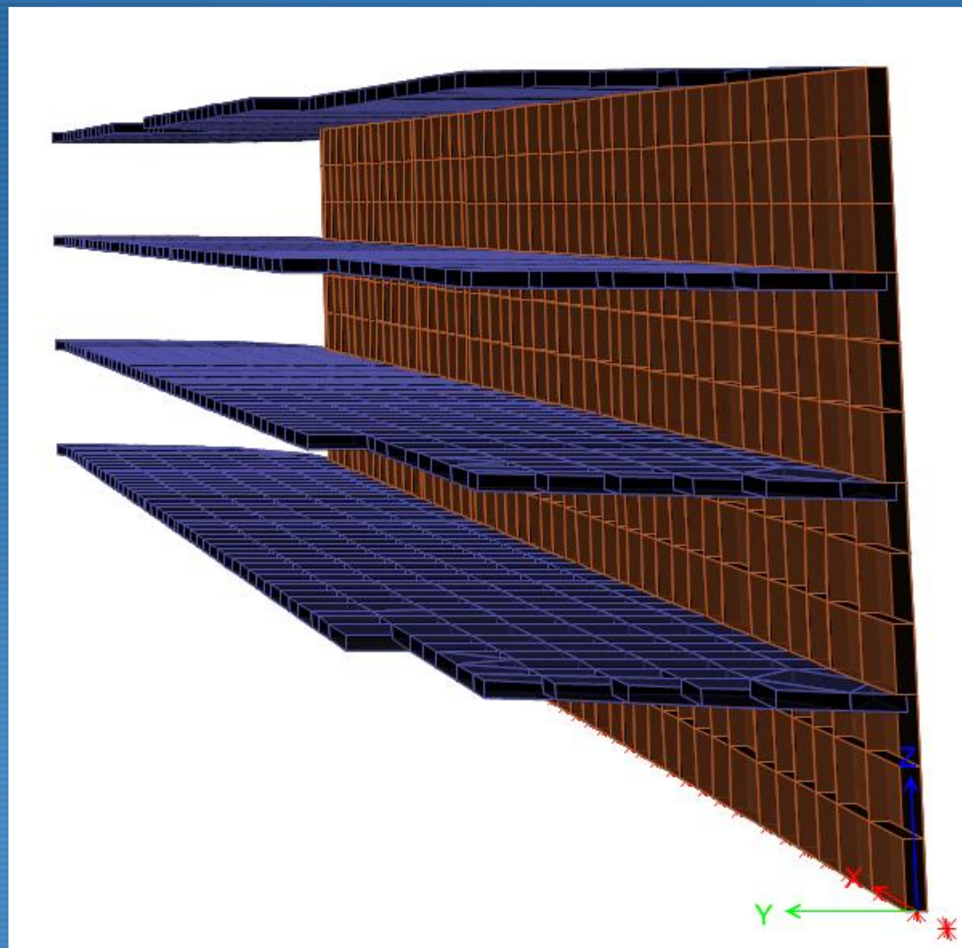
Static Design



Static Design: Walls

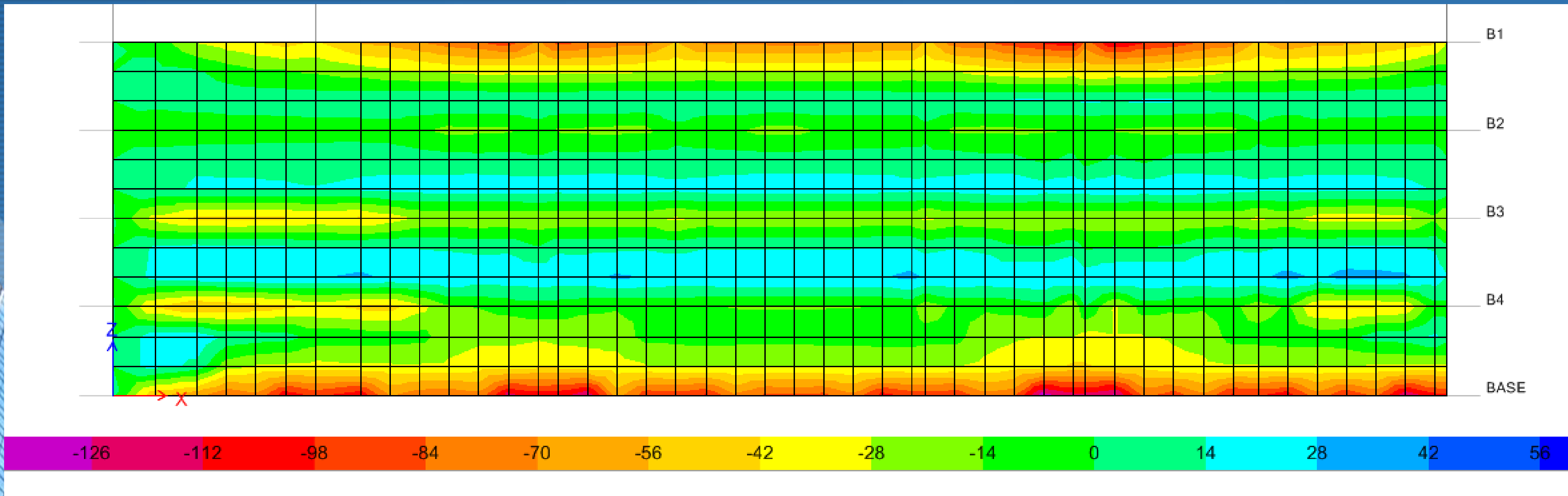
- The governing forces in walls are M_{22} and V_{23}.
- Maximum M22 value found = 115 kN-m/m.
- Maximum V23 value found = 128 kN-m/m.
- These values occur at the bottom of the wall.

Static Design: Walls



Basement walls are supported by slabs

Static Design: Walls



M22 diagram for external wall

$$\rho = \frac{.85f'c}{fy}\left(1-\sqrt{1-\frac{2.61Mu}{bd^2f'c}}\right)$$

This equation provides a steel ratio of **0.31%** for the maximum bending value.

Static Design: Walls

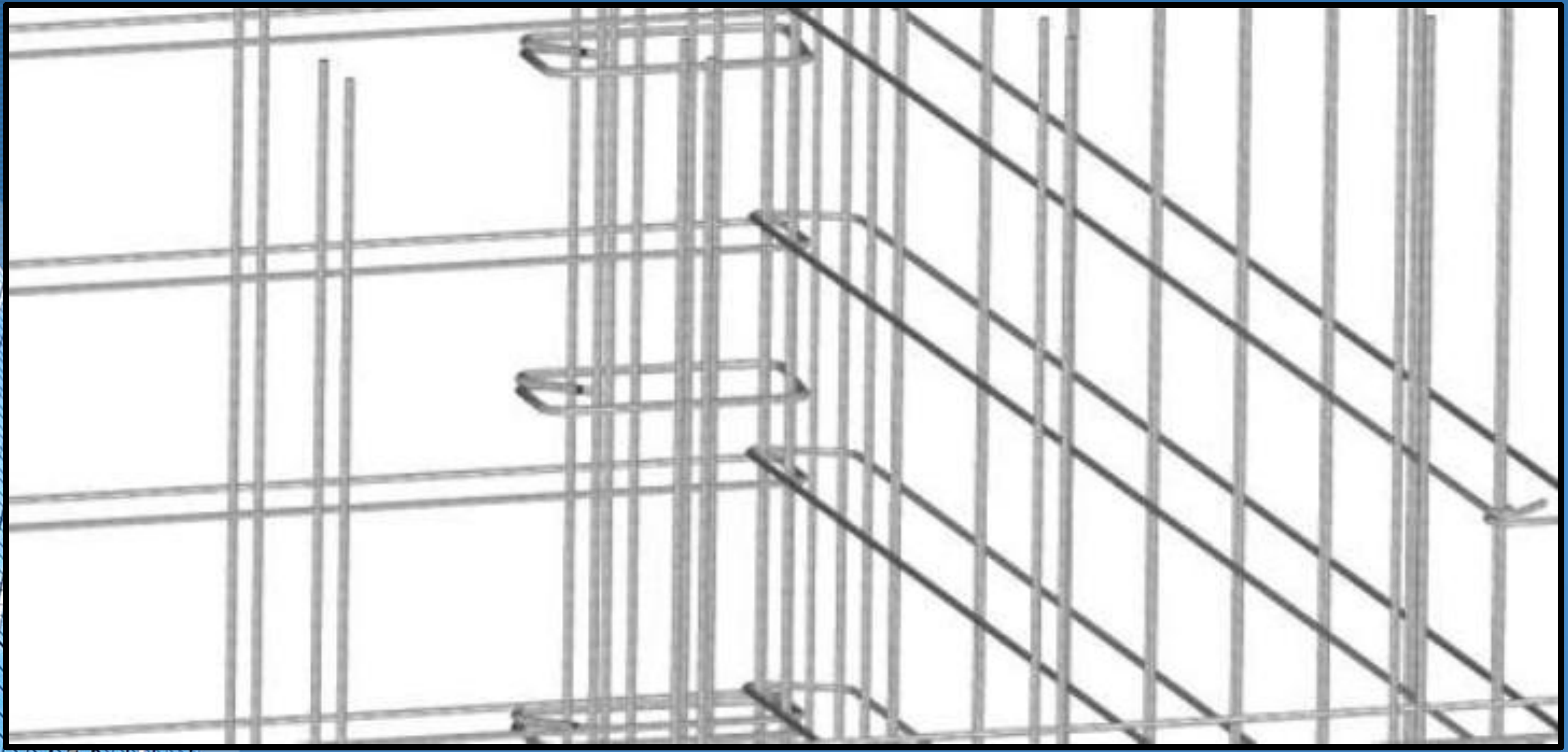
Story	Pier Label	Station	Design Type	Edge Rebar	End Rebar	Rebar Spacing mm	Min. Reinf. %	Current Reinf. %	Pier Leg mm	Leg X1 mm	Leg Y1 mm	Leg X2 mm	Leg Y2 mm	Shear Rebar mm^2/m
B1	P30	Top	Uniform	12	14	250	0.25	**0.31**	Top Leg 1	47225	346	48133	769	750
B1	P30	Bottom	Uniform	12	14	250	0.25	**0.31**	Bottom Leg 1	47225	346	48133	769	750
B2	P30	Top	Uniform	12	14	250	0.25	**0.31**	Top Leg 1	47225	346	48133	769	750
B2	P30	Bottom	Uniform	12	14	250	0.25	**0.31**	Bottom Leg 1	47225	346	48133	769	750
B3	P30	Top	Uniform	12	14	250	0.25	**0.31**	Top Leg 1	47225	346	48133	769	750
B3	P30	Bottom	Uniform	12	14	250	0.25	**0.31**	Bottom Leg 1	47225	346	48133	769	750
B4	P30	Top	Uniform	12	14	250	0.25	**0.31**	Top Leg 1	47225	346	48133	769	750
B4	P30	Bottom	Uniform	12	14	250	0.25	**0.31**	Bottom Leg 1	47225	346	48133	769	750

Static Design: Walls

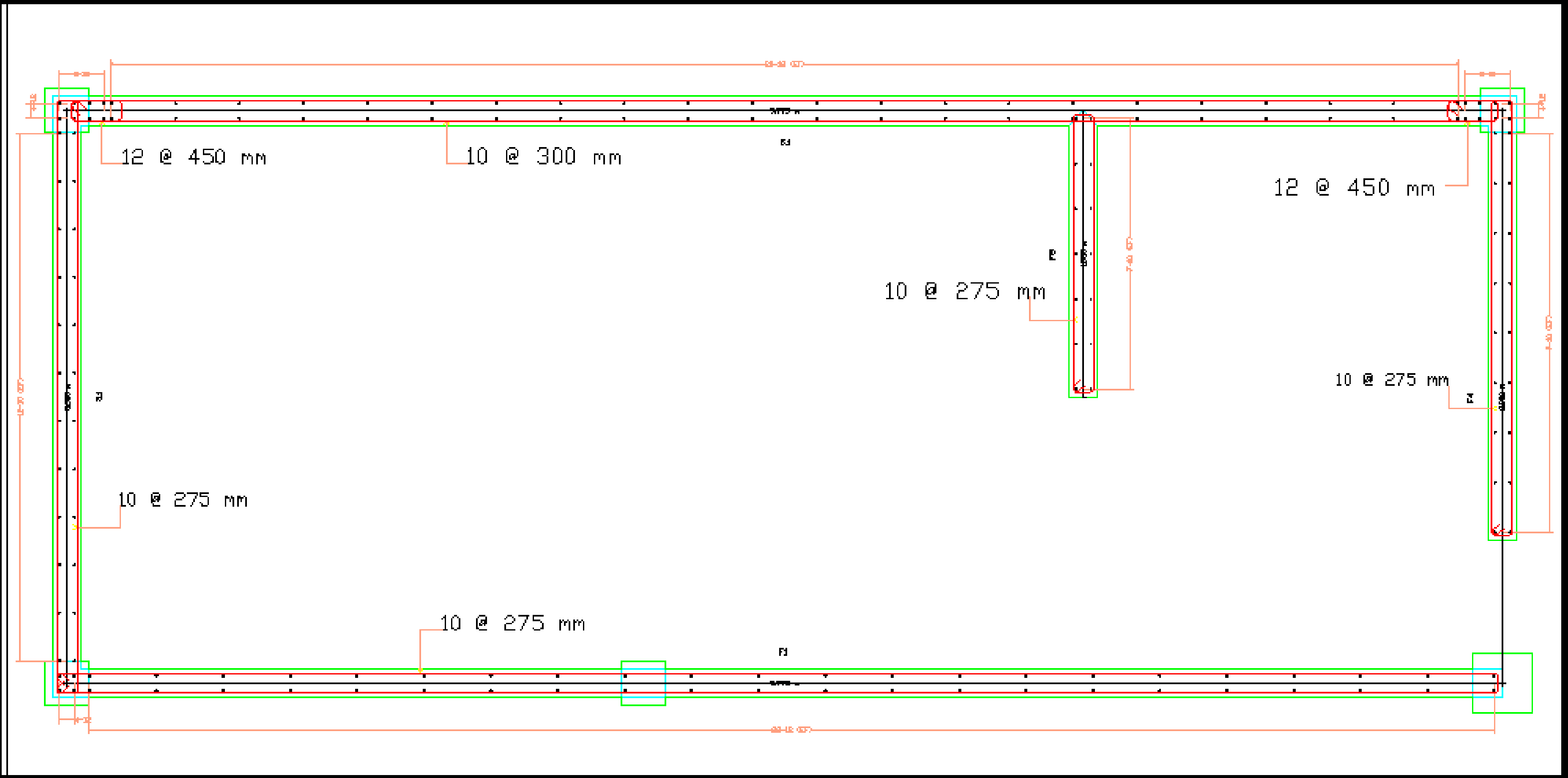
- The "Uniform" reinforcement option is chosen in ETABS 2013, means that steel ratio is constant along the wall.

- Rebar preferences are selected in ETABS in order to generate steel detailing.

Static Design: Walls



Static Design: Walls



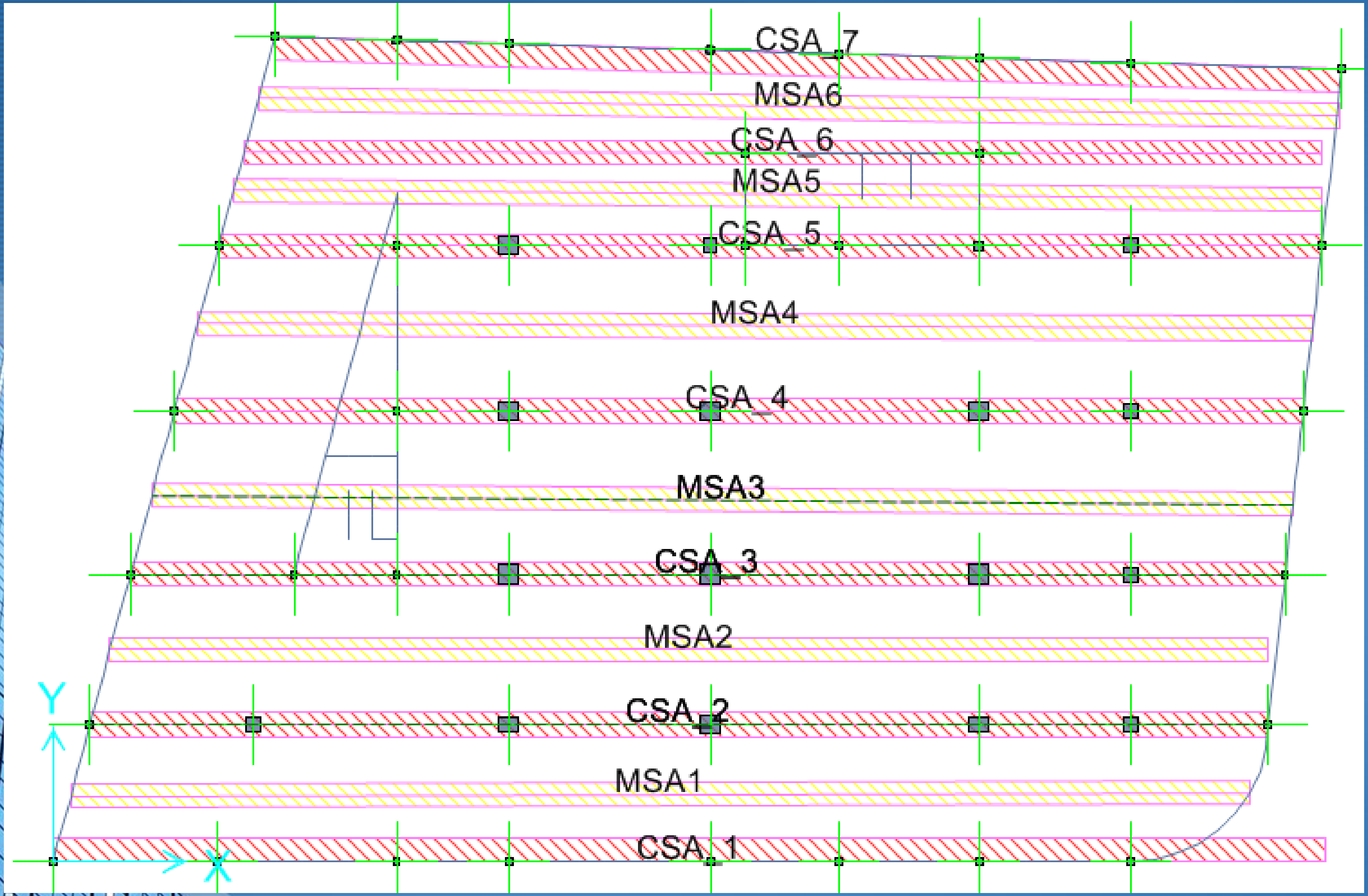
Static Design: Slabs

- Slabs are designed using SAFE V12.

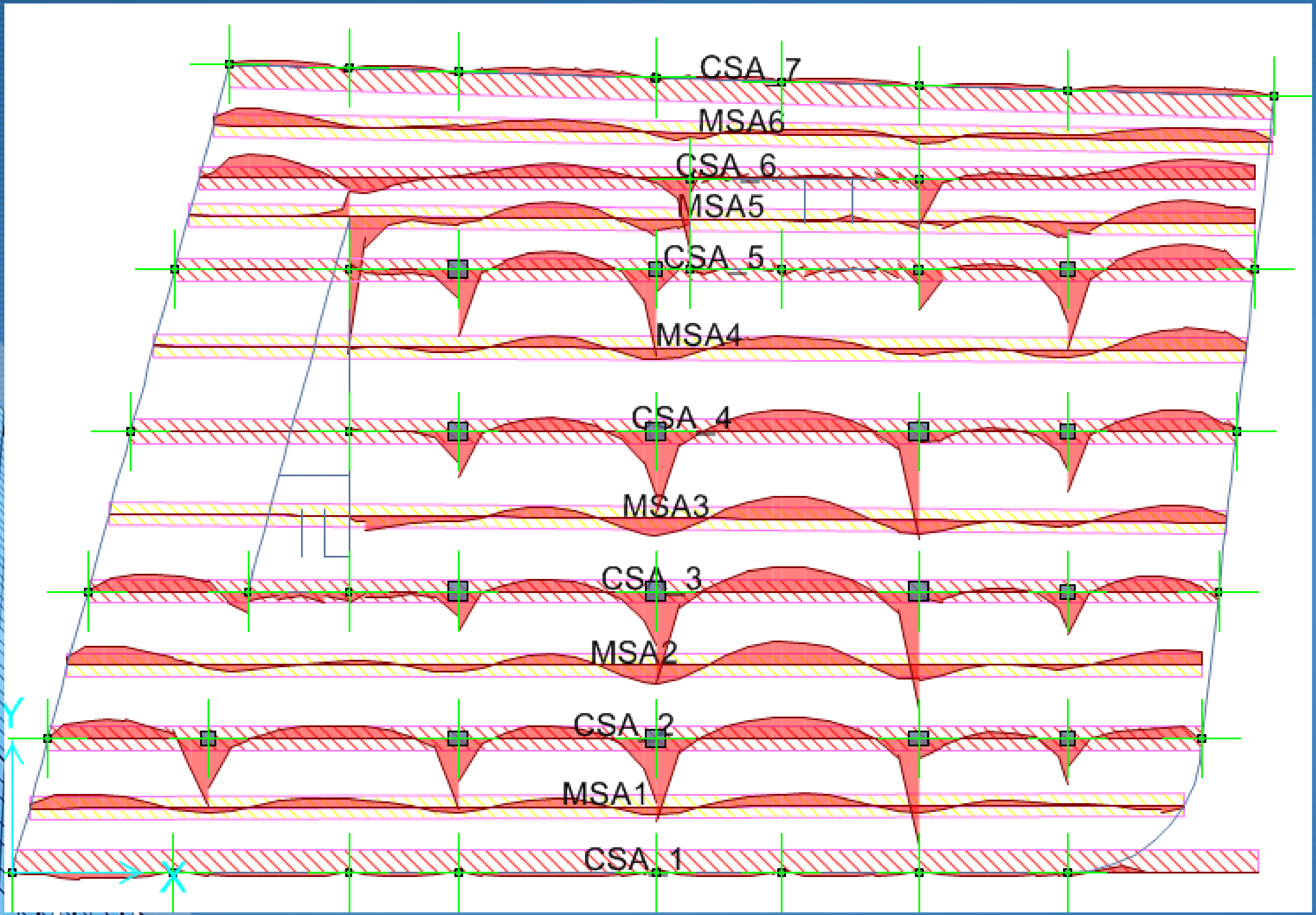
- SAFE finds forces acting on slab strips, provides reinforcement ratios and rebar detailing.

- Design is based on the Ultimate Method and complies with ACI 318-08 Code.

Static Design: Slabs



Static Design: Slabs



Static Design: Slabs

Conc Width m	FTopMoment kN.m	FTopArea mm^2	FTopAMin mm^2	FBotMoment kN.m	FBotArea mm^2	FBotAMin mm^2	V Force kN	VArea mm^2/m	Status	Global X m	Global Y m
0.5177	-34.4186	491.497	240.933	2.6667	135.259	0	45.157	0	OK	51.71601	12.042
1	-0.1726	374.834	465.396	14.0022	277.36	0	86.941	0	OK	51.004	12.042
1	0	146.421	0	35.7218	485.884	465.396	30.496	0	OK	50.262	12.042
1	-127.3975	1669.485	465.396	0.0193	0	0	157.117	861.845	OK	45.262	12.042
1	-60.5339	765.834	465.396	0	0	0	157.117	861.845	OK	44.867	12.042
1	-10.9128	134.806	465.396	1.1423	14.048	0	52.217	0	OK	43.867	12.042
1	0	0	0	9.9952	123.418	465.396	15.758	0	OK	42.867	12.042
1	0	0	0	9.9846	123.286	465.396	11.761	0	OK	41.867	12.042
1	-3.09	38.034	465.396	1.2232	15.043	0	28.424	0	OK	40.867	12.042
1	-36.8601	461.063	465.396	0.0422	0	0	28.424	0	OK	39.867	12.042
1	-357.0576	5161.406	465.396	0	946.911	0	340.187	2820.612	OK	38.867	12.042
1	-82.3367	1053.254	465.396	0	0	0	340.187	2820.612	OK	38.012	12.042
1	-14.5507	180.049	465.396	2.8689	35.309	0	67.778	0	OK	37.012	12.042
1	-0.02	0	0	34.8068	434.843	465.396	41.713	0	OK	36.012	12.042
1	0	0	0	57.5723	727.293	465.396	26.256	0	OK	35.012	12.042
1	0	0	0	69.0246	876.982	465.396	13.978	0	OK	34.012	12.042
1	0	0	0	71.0779	904.01	465.396	4.913	0	OK	33.012	12.042
1	0	0	0	69.4167	882.139	465.396	12.769	0	OK	32.588	12.042
1	0	0	0	58.7434	742.518	465.396	24.532	0	OK	31.588	12.042
1	0	0	0	37.6057	470.443	465.396	38.952	0	OK	30.588	12.042
1	-7.3336	90.442	465.396	4.0817	50.263	0	56.092	0	OK	29.588	12.042
1	-66.5377	844.326	465.396	0	0	0	231.155	1212.478	OK	28.588	12.042
1	-265.5921	3801.853	465.396	0	0	0	231.155	1212.478	OK	27.588	12.042
1	-105.2553	1362.75	465.396	0	0	0	163.827	861.845	OK	27.126	12.042
1	-32.4039	404.358	465.396	0.0217	0	0	72.5	0	OK	26.126	12.042
1	-0.4702	5.781	0	10.8523	134.055	465.396	36.255	0	OK	25.126	12.042
1	0	0	0	28.1028	349.968	465.396	20.927	0	OK	24.126	12.042

B4 Slab forces

Static Design: Mat Foundation

- Using service combination D+L, the base reaction is equal to 162,500 kN.

- Area of foundation= 162,500 kN/ 250 kN/m2
  = 650 sq meters.

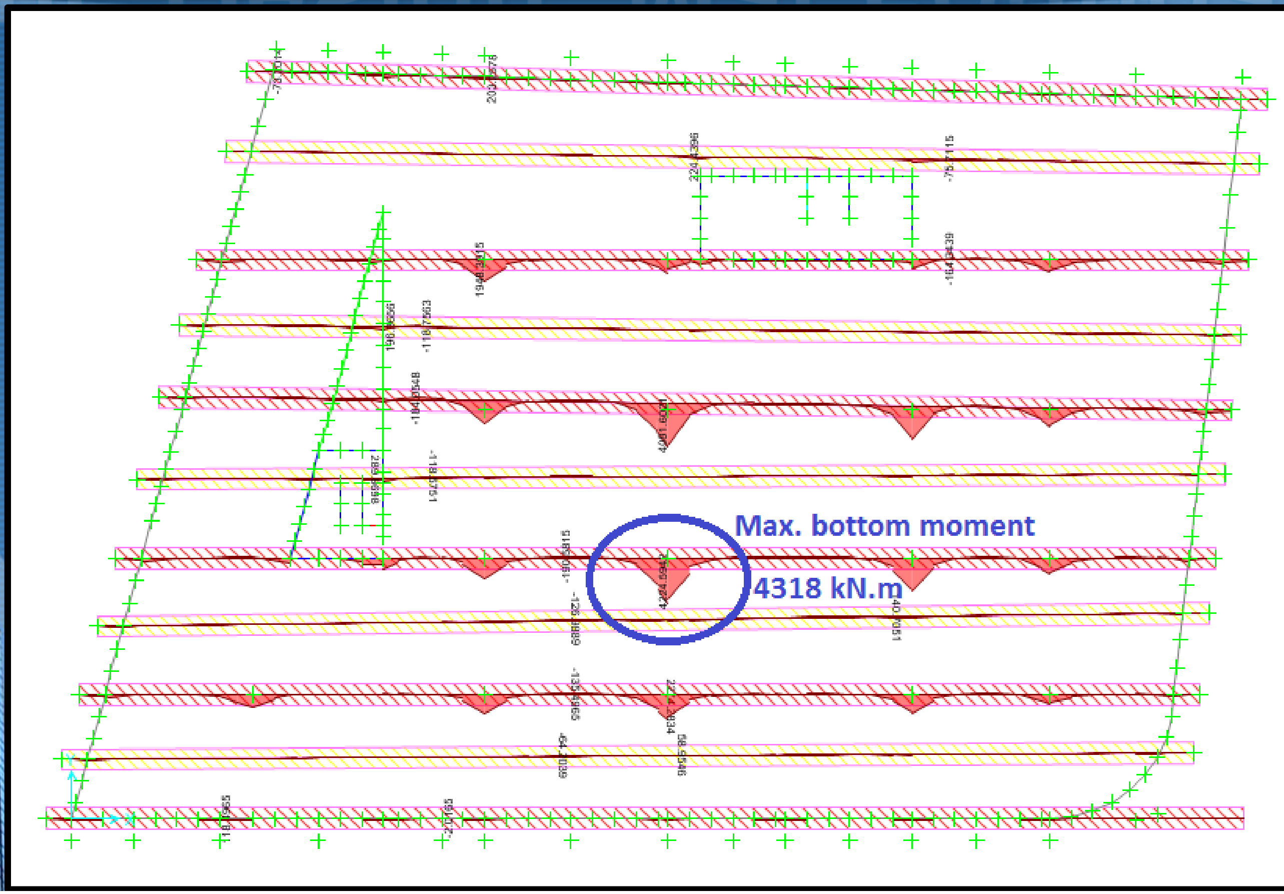
- Punching shear required increasing drop panel thickness from 60cm to 120cm.

Static Design: Mat Foundation

Area	Surface Pressure (kN/m^2)
F9	-20.15
F9	-81.08
F9	-72.42
F9	-18.83
F10	-81.08
F10	-173.56
F10	-162.77
F10	-72.42
F11	-173.56
F11	-238.77
F11	-233.9
F11	-162.77
F12	-238.77
F12	-244.54
F12	-237.08
F12	-233.9
F13	-188.48

- Soil pressure values are below the maximum allowable limit of 250 kN/m2.
- No uplift force was found.

Static Design: Mat Foundation



Maximum positive moment = 4318.3 kN-m occurs in column-strip A at section with thickness of 120 cm.

Maximum negative moment = 283.6 kN.m occurs in column-strip B at section with thickness of 30 cm.

Earthquake Analysis & Design

- We want to investigate the dynamic behavior of The Gateway Building, then re-design the structural elements.

- The UBC-97 Code is used for earthquake analysis and design.

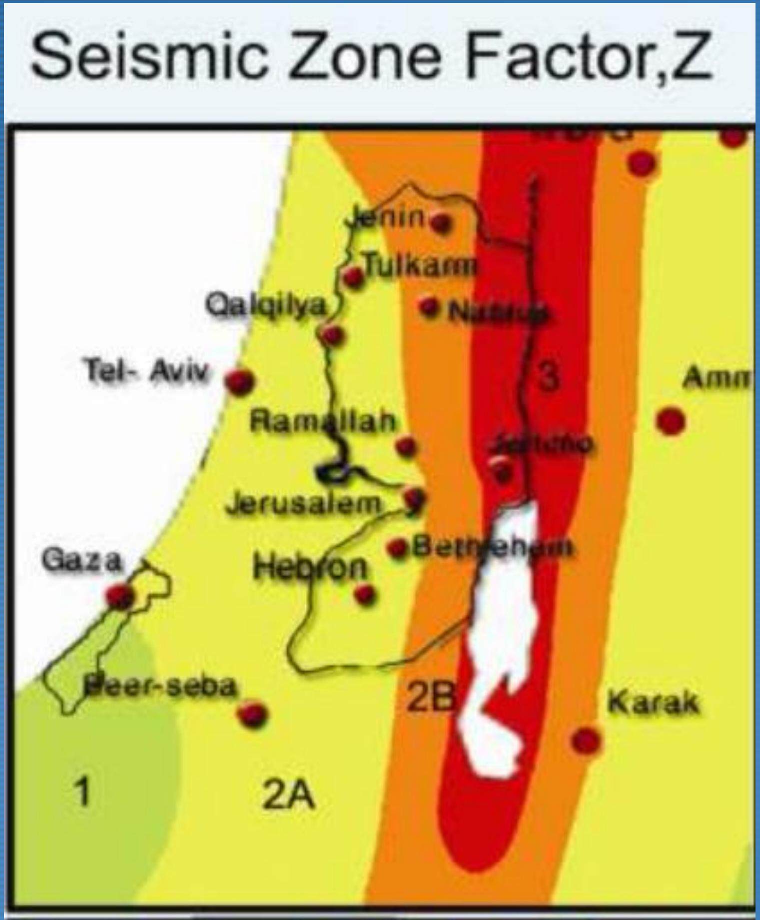
- The purpose of design is to maintain life safety under potential earthquakes.

Earthquake Analysis & Design

- <u>Geology:</u>
  - The building is located in Ramallah and is built on a rock layer.
  - This zone is classified as 2A, which is considered a moderate-risk zone.
  - Ca and Cv are both equal to 0.15.
  - Soil is classified as SB.

Earthquake Analysis & Design

- Seismic Zone Factor Map:



Zone	1	2A	2B	3
Z	0.075	0.15	0.20	0.30

Earthquake Analysis & Design

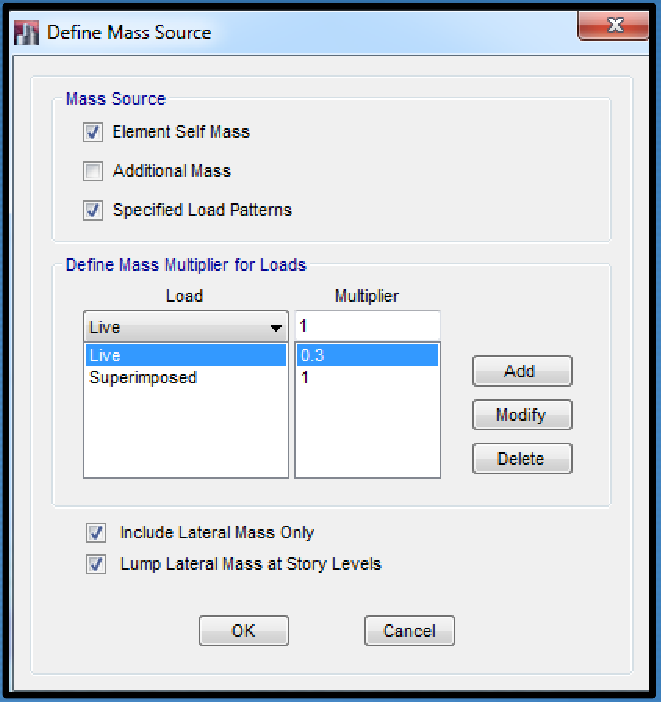
- Modal Analysis:
  - Eigenvector modal analysis is used to determine the vibration modes of the structure.
  - Available modes are equal to the number of mass degrees of freedom in the structure, but we are interested in the first modes only.
  - Modal analysis results are reported as Eigen-values.
  - An Eigenvalue is the square of the circular frequency (ω).

$$\omega = \mathrm{sqrt}(K/M)$$

Where K is stiffness and M is mass.

Earthquake Analysis & Design

- The mass participating in the dynamic behavior of the structure comprises of self-mass of the structure plus superimposed dead load and a portion of live load; 0.3.



Earthquake Analysis & Design

Mode	Period (Seconds)	Frequency (cycle/second)	Circular Frequency (rad/sec)	Eigenvalue (rad^2/sec^2)
1	1.102	0.907	5.7019	32.5119
2	0.931	1.074	6.748	45.5361
3	0.511	1.956	12.2874	150.9794
4	0.268	3.736	23.4749	551.0726
5	0.227	4.408	27.6991	767.2421
6	0.143	6.974	43.82	1920.1896
7	0.128	7.793	48.9648	2397.5558
8	0.121	8.296	52.1273	2717.2537
9	0.097	10.301	64.7201	4188.687
10	0.088	11.346	71.2888	5082.0939
11	0.083	12.116	76.125	5795.0088
12	0.074	13.576	85.2979	7275.7348
13	0.069	14.469	90.9094	8264.5268
14	0.065	15.368	96.5631	9324.4252
15	0.063	15.997	100.5101	10102.2897
16	0.059	16.899	106.1809	11274.3828
17	0.058	17.216	108.1725	11701.2977
18	0.058	17.374	109.1661	11917.2423
19	0.054	18.58	116.7427	13628.8596
20	0.053	18.872	118.5737	14059.7315

Earthquake Analysis & Design

- The UBC-97 code states that at least 90 % of the participating mass of the structure is included in the calculations for each principal horizontal direction.

- 20 modes had to be investigated in order to satisfy this code requirement.

Direction	Static	Dynamic
UX	99.98	93.54
UY	99.98	93.49

Earthquake Analysis & Design

- Equivalent Lateral Load Method:
  - This method replaces dynamic loads with equivalent static loads.
  - ETABS 2013 is used to find these loads, using the following input:

Parameter	Value
T (seconds)	1.1
R	4.5
Soil profile type	S_B
Z	0.15
C_a	0.15
C_v	0.15
I	1.0

- **T, structure's SDOF period (sec)**
- **R, Overstrength factor.**
- **S_B: soil profile type for rock.**
- **Ca: Seismic acceleration factor.**
- **Cv: seismic velocity factor.**
- **I: importance factor.**

Earthquake Analysis & Design

- UBC-97 has an equation to estimate T:

$$T = C_t \, (h_n)^{3/4}$$

$C_t = 0.03$

$h_n = 140$ (building height in feet).

So, T= 1.22 seconds

ETABS 2013 result for T is 1.1 sec which is not significantly different than UBC-97 equ. Result.

Earthquake Analysis & Design

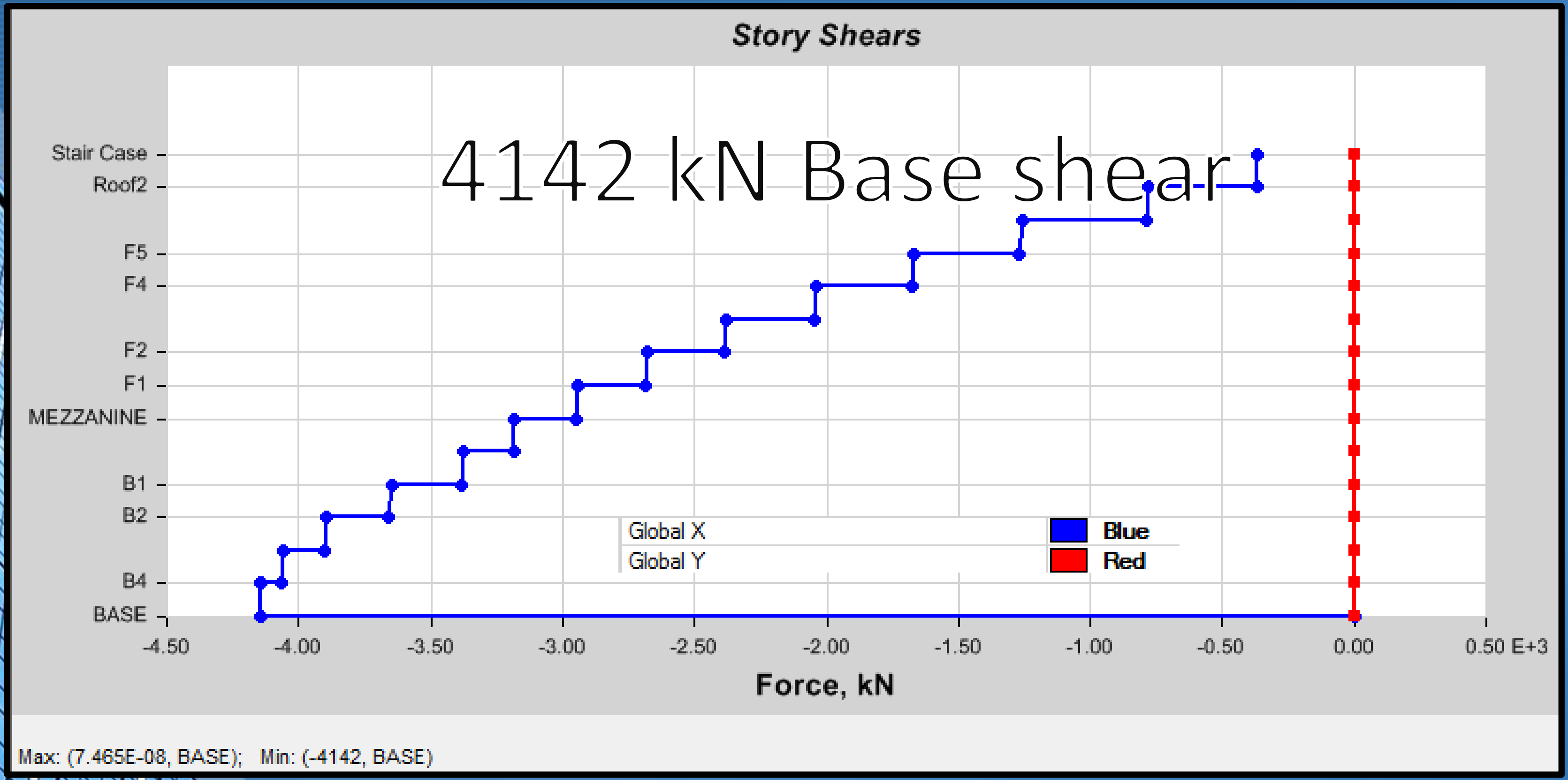
- R, overstrength factor: this factor considers ductility of the lateral-force resisting systems.

- For concrete shear walls R=4.5

- R factor reduces the design forces.

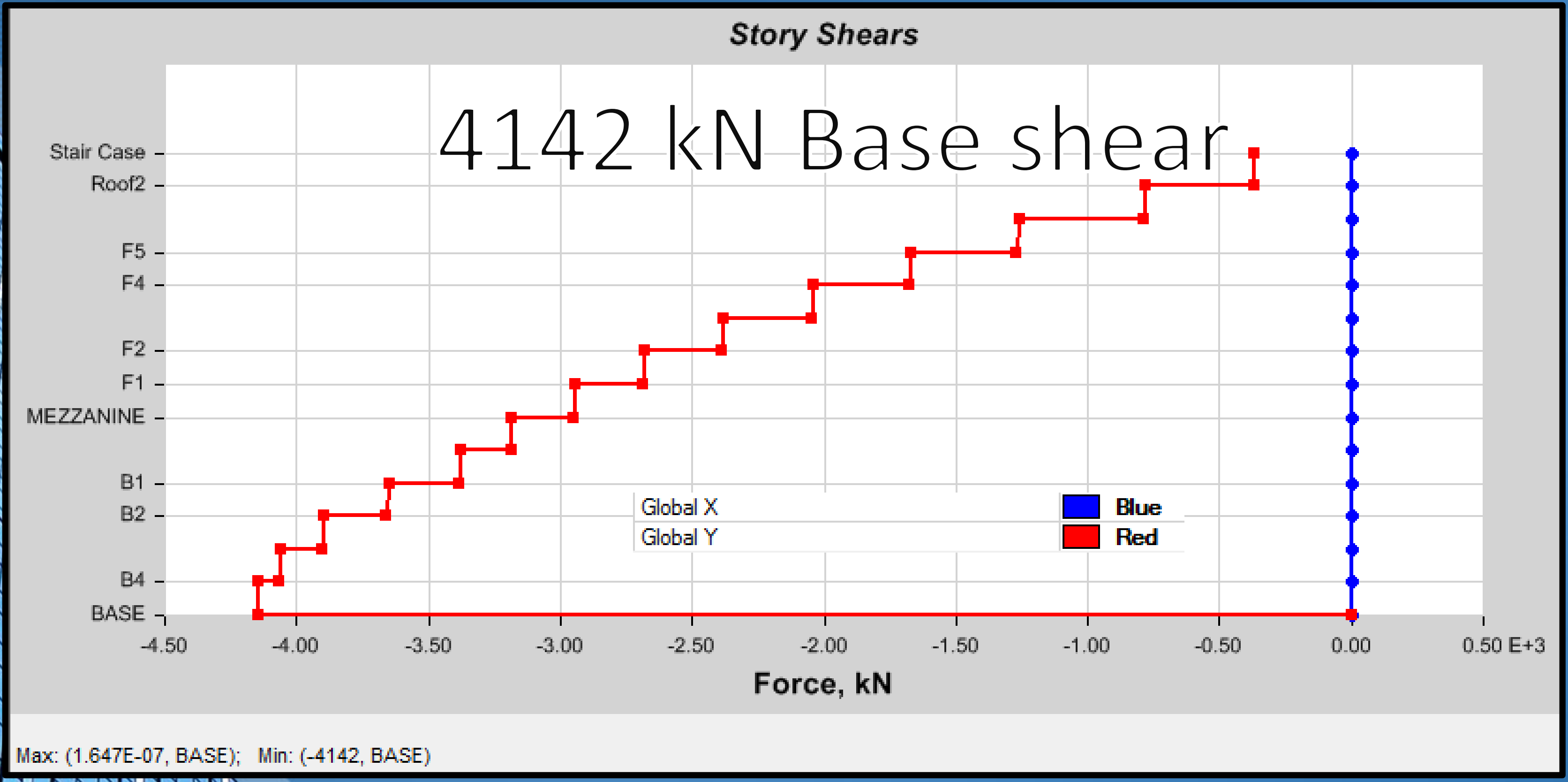
Earthquake Analysis & Design

- ELL in the X-direction



Earthquake Analysis & Design

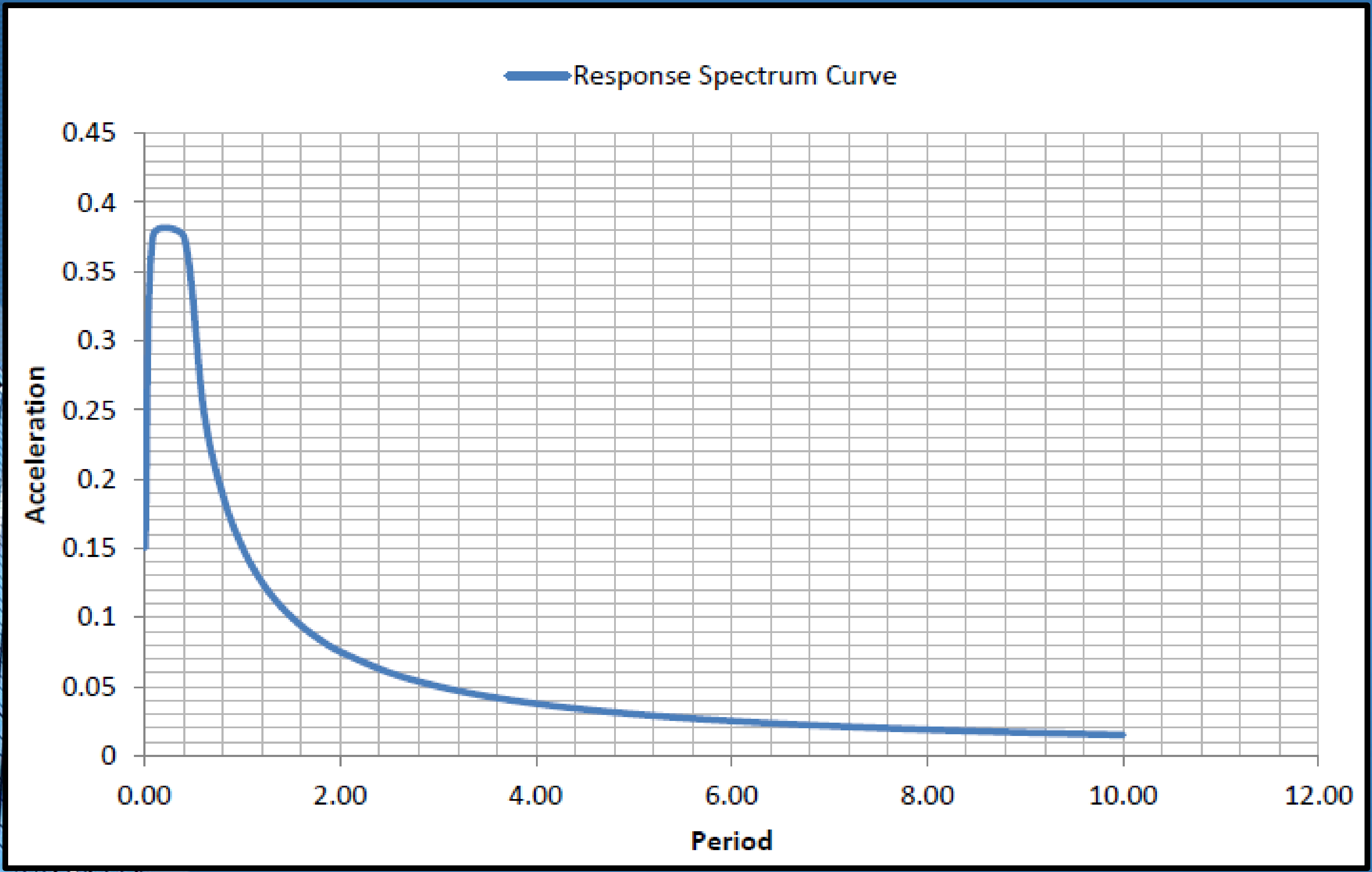
- ELL in the Y-direction



Earthquake Analysis & Design

- Response Spectrum Analysis:
  - ELLM may be not enough to predict lateral forces specially for irregular structures.
  - Response spectrum analysis utilizes the peak dynamic response of all effective modes.
  - The RS curve is taken from the UBC-97 Code for the location studied in this project.

Earthquake Analysis & Design



Earthquake Analysis & Design

- Modal combination had to be defined because peak responses occur at different times.
- CQC *(complete quadratic combination)* method is used for modal combination.
- For directional combination, the SRSS (*Square Root of the Sum of the Squares*)

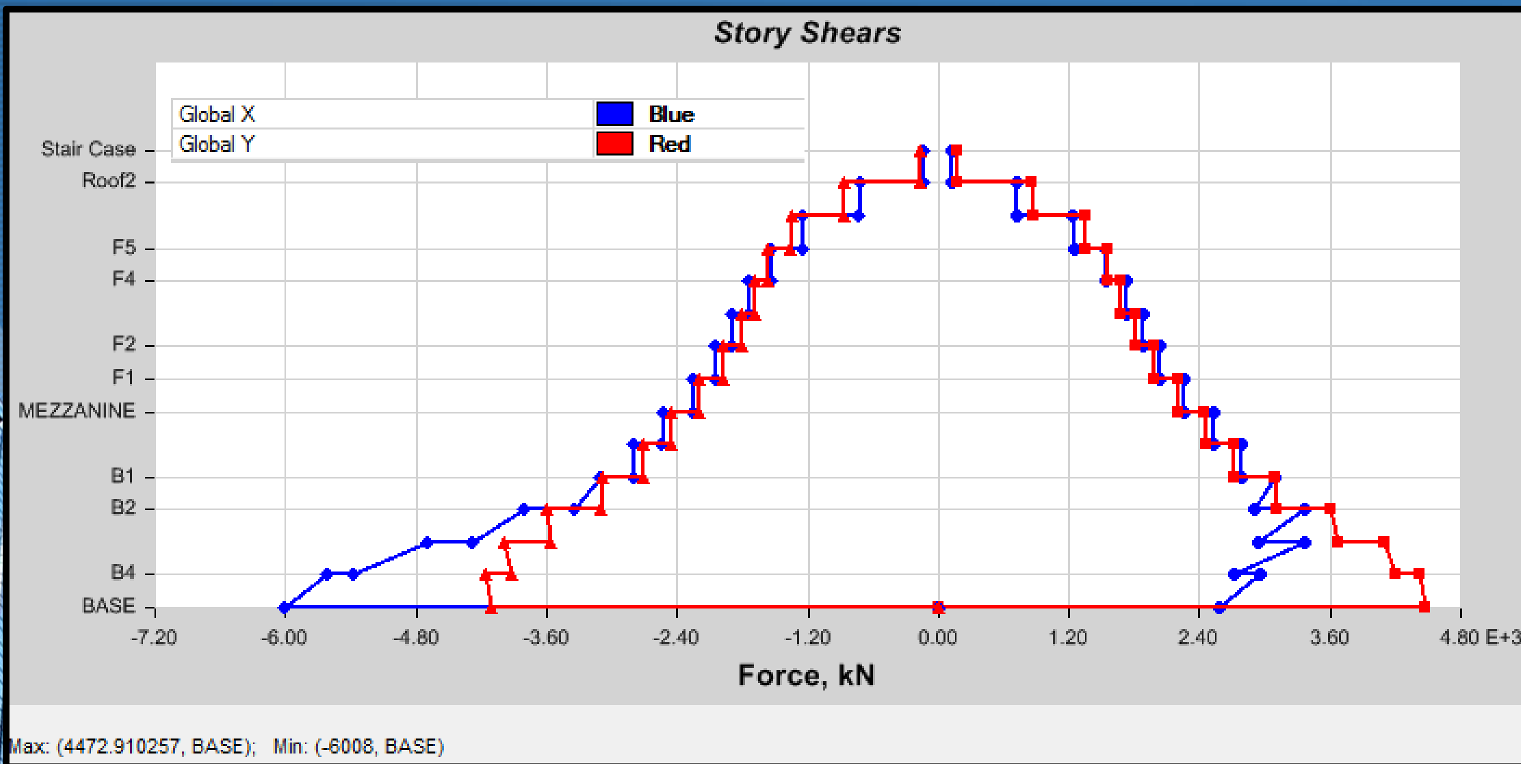
Earthquake Analysis & Design

- Response spectrum curve is scaled up by a factor.
- Scaling factor= ELLM force/RS force

- RS in X-direction is scaled by 2.7
- RS in Y-direction is scaled by 2.8

- The scaling procedure is taken from the UBC-97 code.

Earthquake Analysis & Design



Response Spectrum story shears due to scaled RS curve

Earthquake Analysis & Design

Comb5: U=Envelope (Comb1, Comb2, Comb3, Comb4)
Comb6: U=1.2D + 1.0L + 1.0S + 1.0H + 1.0E
Comb7: U=1.2D + 1.0L + 1.0S + 1.0H - 1.0E
Comb8: U=Envelope(Comb5, Comb6, Comb7)

Comb8 is used for design

Earthquake Analysis & Design

- Story Drifts:
  - The lateral displacement of one level of a multistory structure relative to the level below.
  - UBC-97 limits inelastic drift to a maximum of 0.02. This if for building with period greater than 0.7 seconds.
  - Design level drift ratio $\boldsymbol{\Delta_{RS} = (\Delta_2 - \Delta_1)/h}$
  - Inelastic drift ratio $\boldsymbol{= 0.7 * R * \Delta_{RS}}$

Earthquake Analysis & Design

Story	Drift X (mm)	Drift Y (mm)	Drift Ratio X	Drift Ratio Y
Stair Case	0.9	2	0.0003	0.0007
Roof2	1.3	2	0.0004	0.0007
Roof1	1.5	2.2	0.0005	0.0007
F5	1.5	2.3	0.0005	0.0008
F4	1.5	2.3	0.0005	0.0008
F3	1.5	2.2	0.0005	0.0007
F2	1.5	2.1	0.0005	0.0007
F1	1.4	2	0.0005	0.0007
MEZZANINE	1.3	1.8	0.0004	0.0006
GF	1	1.3	0.0003	0.0004
B1	0.3	0.4	0.0001	0.0001
B2	0.2	0.3	0.0001	0.0001

Earthquake Analysis & Design

- Max. inelastic drift ratio= 0.7*0.0008*4.5

  = **0.003 << 0.02**

- Drift ratio are within the allowable limit according to the UBC-97 code.

Earthquake Analysis & Design

- Mat foundation design:
  - Lateral forces resulted in soil pressure that exceeded the maximum allowable, uplift forces were found as well.

MaxPress kN/m²	MinPress kN/m²	GlobalXMax m	GlobalYMax m	GlobalXMin m	GlobalYMin m
8.98	-389.72	33.012	16.042	27.588	13.042

Mat thickness is increased to 60cm, uplift forces are gone and the pressure on soil is within the allowable limit.

MaxPress kN/m²	MinPress kN/m²	GlobalXMax m	GlobalYMax m	GlobalXMin m	GlobalYMin m
-22	-241	8.410	35.658	14.426	17.042

Earthquake Analysis & Design

- Slabs Design:
  - Slabs thickness of 25 cm is adequate for resisting both static and dynamic forces.
  - For static loads design, all slabs required 40cm drop panels except for the basement slabs.
  - Under dynamic loading, all slabs required drop panels for resisting punching shear.

Earthquake Analysis & Design

Point	Global X	Global Y	Status	Ratio	V_U
2088	19.126	25.842	OK	0.825018	556.497
2089	19.126	18.892	OK	0.657269	244.066
2090	19.126	12.042	OK	0.634517	217.287
2091	19.126	5.742	**Failed**	1.176682	650.936
2092	27.588	25.842	OK	0.926061	496.443
2093	27.588	18.892	OK	0.779566	720.752
2094	27.588	12.042	OK	0.792111	716.204
2095	27.588	5.742	OK	0.927096	738.724
2096	38.867	12.042	**Failed**	1.150031	629.302
2097	38.867	5.742	**Failed**	1.402556	662.195
2098	38.867	18.892	**Failed**	1.024411	613.127
2099	45.262	25.842	**Failed**	1.119385	715.722

Design Summary

- Mat foundation thickness is 60cm with 120-cm drop panels under columns.
- Largest column section used is 80x80cm, and the smallest is 30x30cm.
- Underground external walls have a thickness of 30cm, while interior walls that serve as staircases and elevator cores have 20cm thickness

Design Summary

- All slabs have thickness of 25cm and drop panels protruding 15cm below slab.
- Maximum inelastic story drift ratios are within allowable limits.
- Local failures in some structural elements may occur, but this cannot be determined using this type of analysis. Performance-based analysis could be used.

Conclusion

- Flat-plate slab systems are very efficient and can be used for relatively long spans in commercial buildings. This practice is proven by eliminating numerous columns that were considered superfluous.

- Column-drop panels are good for both increasing punching shear capacity of the section and for negative moment resistance. They have also been found to reduce deflection along the span.

Conclusion

- For numerical modeling, the shell-element is best used for modeling shear walls and slabs for they take into consideration both in-plane and out-of-plane bending behavior in addition to axial forces.
- The soil supporting the structure did undergo excessive pressures and tensile forces at some locations due to the lateral forces induced by the earthquake, therefore, the mat thickness had to be doubled.