100 Eleventh Avenue

New York, New York

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Revised Senior Thesis Proposal

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Executive Summary

100 Eleventh Avenue is a 22-story, 148,000 sf residential building located in Manhattan's West Chelsea District, containing 6,000 sf of street-level retail space in addition to its 55 condominium units. Its defining feature is its facade, a panelized curtainwall system consisting of 1650 windows, each a different size and uniquely oriented in space. The building's superstructure is cast-in-place concrete, with a two-way flat plate floor system. Lateral loads are resisted by shear walls and seven long columns.

The following document proposes an in-depth study of using post-tensioning as a means of reducing the slab thickness of portions of 100 Eleventh Avenue's floor system. Typical slab thickness is 9", with the exception being along the south and west-facing perimeter, where 34' spans and the building facade load dictate an 18.5" slab. This thickened portion is a 9.5'-wide strip along the perimeter of the typical floor, but extends outward on the lower six levels to form the building's balcony system. The proposed thesis will include a redesign of this portion of the slab using post-tensioned tendons and will ultimately compare the redesign to the existing system using criteria such as cost, weight, appearance, and practicality. Because portions of the thickened slab cantilever outwards as balconies, the balcony system will also need to be analyzed to ensure the redesigned slab is sufficiently strong and meets deflection requirements. RAM Concept, in combination with hand calculations, will be used to redesign the system.

In addition to post-tensioning the slab perimeter, post-tensioning will also be looked at to reduce the thickness of a transfer slab found on the 19th floor. A setback requires several columns to transfer at the 19th level. The existing slab is 18.5" thick and reinforced with #10 @ 6" each way on top and bottom and is designed to transfer the column forces. The proposed thesis will study the use of post-tensioned beams as a means of transferring the column forces from the 19th level to the 18th level. Again, RAM Concept will be utilized to redesign the system and will be verified with hand calculations, with the results being compared to the existing design.

In addition to the structural depth described above, the effects of the redesign on the structure's construction process will be used as a breadth topic. Items such as schedule and additional formwork costs will be looked at. Because of 100 Eleventh Avenue's large glass facade, a second breadth study will focus on alternatives to the building's shading system. The current system is made of remote-controlled Lutron roller shades. The intent is to find an alternative system that improves the interior space, while providing adequate shading.

Introduction to 100 Eleventh Avenue

100 Eleventh Avenue is a 22-story, 170,000 sf condominium building located in Manhattan's Chelsea District, a neighborhood adjacent to the Hudson River which is quickly gaining in popularity within the city. 100 Eleventh Avenue will join several other recently completed projects that have helped in revitalizing the area, such as the IAC headquarters designed by architect Frank Gehry, and the High Line, a former elevated rail line running through the area that has been converted into an elevated park.

Dubbed a "vision machine" by its Pritzker Prize-winning architect Jean Nouvel, 100 Eleventh Avenue's defining feature is its facade, a panelized curtainwall system consisting of 1650 windows, each a different size and uniquely oriented in space. Light reflecting off the randomly-oriented windows limits views into the building while still allowing occupants spectacular floor-to-ceiling views of both New York City and the Hudson River. In addition, the lower six floors are enclosed by a second facade offset 16 feet towards the street. As seen in Figure 1 below, the space between the two facades is filled with intricate steel framing and cantilevered walls, columns, and balconies. Trees are suspended in air at varying heights, creating a "hanging garden" and a unique atrium space.

The building's structural system is cast-in-place concrete – common for residential buildings in the city. The ground level contains 6000 sf of retail space, as well as an elevated garden space for the residents, which spans over a junior Olympic-sized pool. Levels 2 through 21 house the residential units, with the penthouse making up the 21st floor, containing an extensive private roof terrace.

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Figure 1: Space within double facade

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Figure 2: View from Westside Highway

Structural System Summary

Foundations

100 Eleventh Avenue is located on a man-made portion of Manhattan Island. Therefore, the shallow bedrock typical of much of the island is not present, and the use of piles and drilled caissons is necessary to effectively transfer vertical and horizontal loads to the earth. 127 piles at 150 ton capacity transfer column loads to the ground. Thirteen of these are detailed to provide a 50 kip tension capacity, as several cantilevered columns may, under certain loading conditions, induce tension in the piles, as seen in Figure 4. In addition, 12 large-diameter caissons are located at the structure's shear wall core, ranging in capacity from 600-1500 ton and providing at least 50 kip in lateral capacity. At the cellar level, a 20" thick mat foundation ties the piles together, while resisting the upward soil pressure. At the building's core, this mat slab thickens to 36".

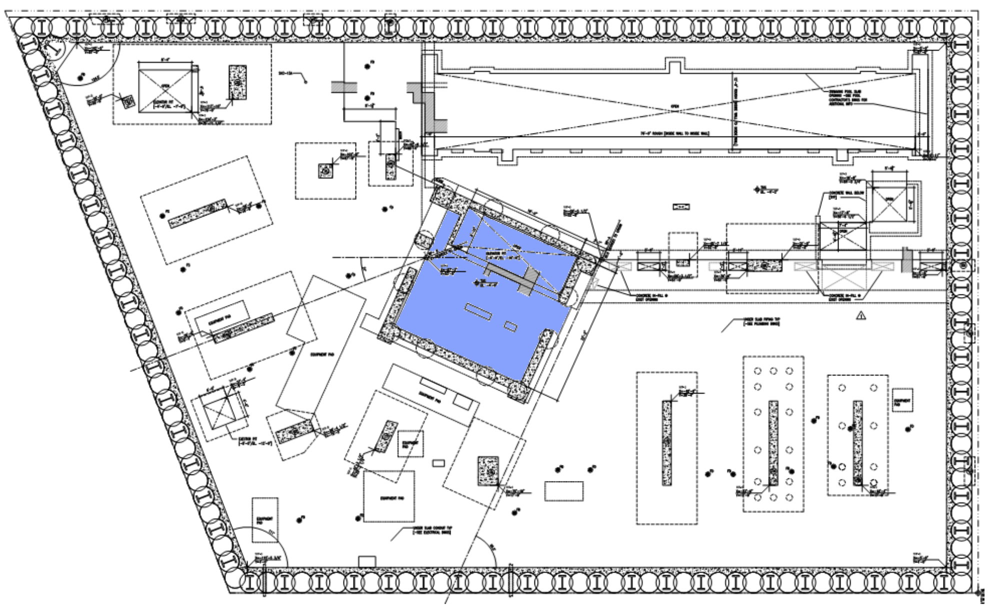


Figure 3: Cellar plan with core denoted

In order to eliminate the cost of underpinning the adjacent structures during excavation, a concrete secant wall system was used instead of traditional foundation walls. As seen in Figure 3, the secant piles are driven around the entire perimeter and resist the lateral soil pressures. The secant wall is braced at its top by the 12" ground floor slab. At all slab steps on the ground floor, torsion beams were used to resist torsion created by the lateral forces from the secant wall.

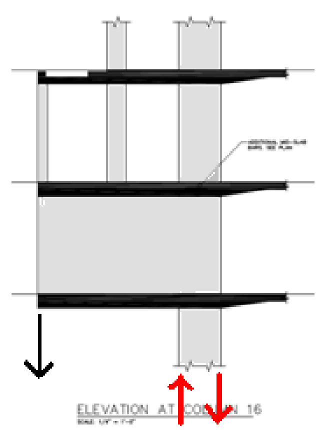


Figure 4: Cantilevered column creating tension in piles

Gravity System

Floor System

Figure 5: Superstructure

100 Eleventh Avenue has a cast-in-place two-way concrete flat-plate floor system. This type of system is common for residential buildings in New York City due to the ease of accommodating column offsets, the minimal floor system thickness, and the sound isolation properties of concrete.

The typical floor is comprised of 9" thick, 5,950 psi concrete reinforced with a basic bottom reinforcing mat of #4 @ 12" E.W. Middle strip bars are also #4 @ 12" unless otherwise noted. Column strip bars are primarily #6 @12". Additional top and bottom bars are used where necessary, likely due to longer spans and varying loads. The slab thickness increases to 12" at the elevator core, where the bottom reinforcing steel is #5 @12" E.W. While no standard span exists, most slab spans range from 18'-23'. Due to increased loads from the curtainwall as well as clear spans as long as 34 feet, the slab thickens from 9" to 18.5" along the curved portion of the building. For appearances, the slab gradually increases in thickness over a distance of 5'-0", as seen in Figure 6 & 7, rather than undergoing an abrupt increase.

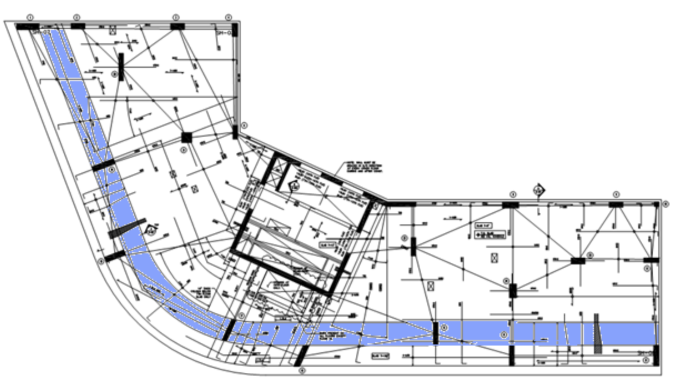


Figure 6: Typical plan with slab thickness transition area highlighted

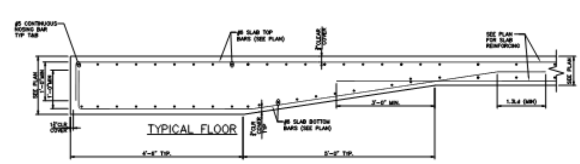


Figure 7: Detail of thickened slab at curved edge

On the lower six floors, balconies begin to cantilever out towards the second street facade. An example of this is shown in Figure 8, where the balcony on the 6th floor extends 9'-10" from the building. Notice that, due to architectural constraints, the balcony has only one corner supported by a column below. To resolve excessive deflection caused by the facade and tree loads, three post-tensioned high-strength Dywidag bars were used, highlighted in green.

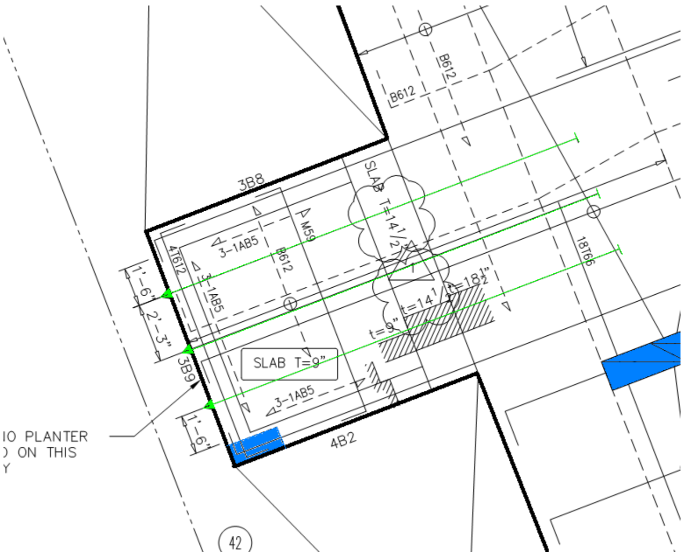


Figure 8: Cantilevered balcony utilizing post-tensioning

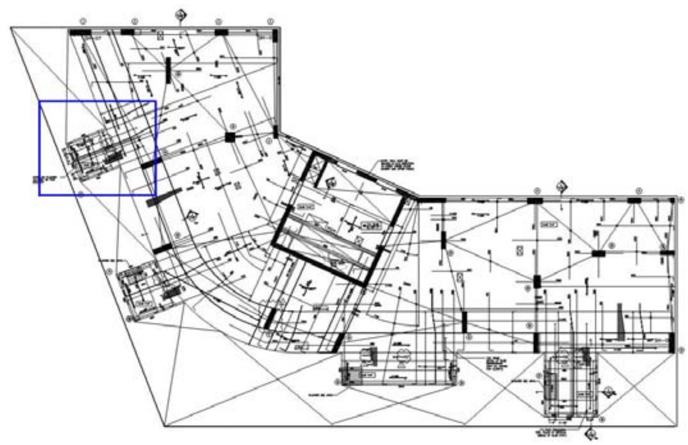


Figure 9: 6th Floor Plan

On the 19th floor, the building sets back 13 feet on the east side, and several columns transfer, as shown in Figure 10. The gravity forces carried by these columns are transferred via an 18.5" thick transfer slab, reinforced with #10 @6" E.W. on both top and bottom of slab.

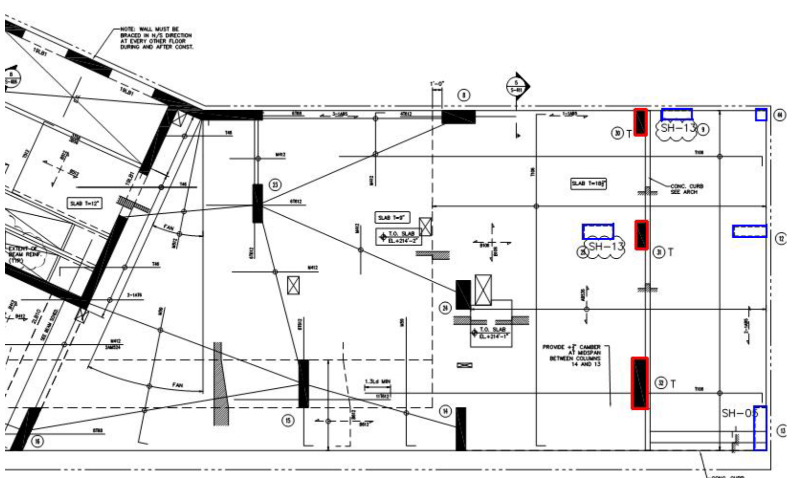


Figure 10: 19th floor transfer slab with red denoting terminated columns and blue denoting new column locations on 18th level below

Columns

Concrete strength for columns supporting the cellar level through the 9th level is 8 ksi; those supporting the 10th through the roof have 7 ksi concrete. As evidenced by the typical floor plan, no regular grid exists. Spans typically range from 18'-23', except on the curved edge portion, where spans of up to 34' exist. Column sizes range widely throughout a single floor, as well as from floor to floor. The majority are 12"-16" wide and 3-4 times as long, resulting in many "long" columns. This allows the columns to be placed within the walls separating individual units. Also, seven of these long columns were designed as part of the lateral system. More discussion on this can be found in the lateral system summary.

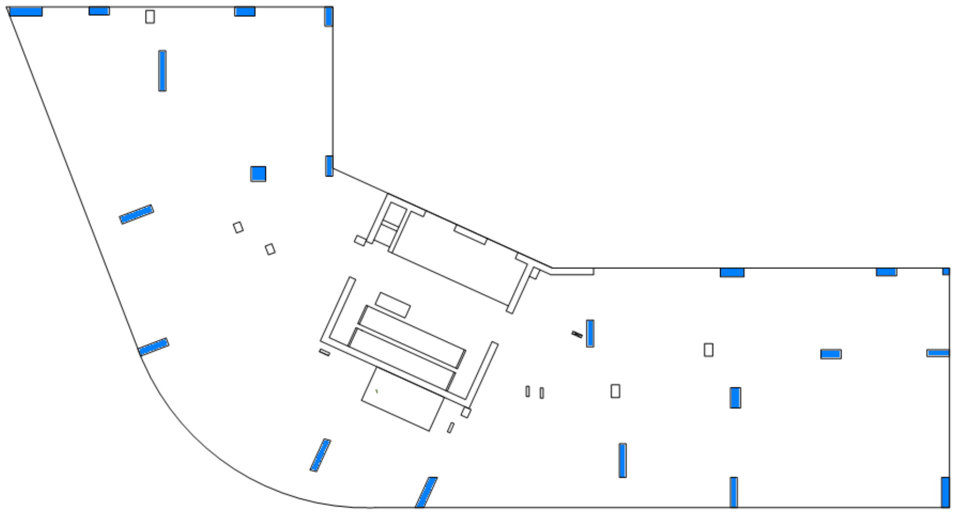


Figure 11: Typical floor column layout

On the lower six floors of the building, these seven long columns also serve as support for the complex balcony system that defines the lower floors, seen in Figure 15. On these floors, intermittent boxes protrude out from the inner facade to meet the outer street facade, which is offset 16' towards the street. On the second level, six of the long columns transfer the balcony system loads by cantilevering outwards 18' to 28', allowing for the column-free space between the double facade system at street level, shown in Figure 1 above. Figure 13 shows the columns supporting the 3rd level, with red denoting the cantilevered portion of the columns. Due to significant tensile forces at the tops of these cantilevered columns, additional reinforcement of six mid-slab #11 Grade 75 bars tie the tops of the columns into the main portion of the slab.

Figure 12: Photo showing portion of cantilevered balcony system

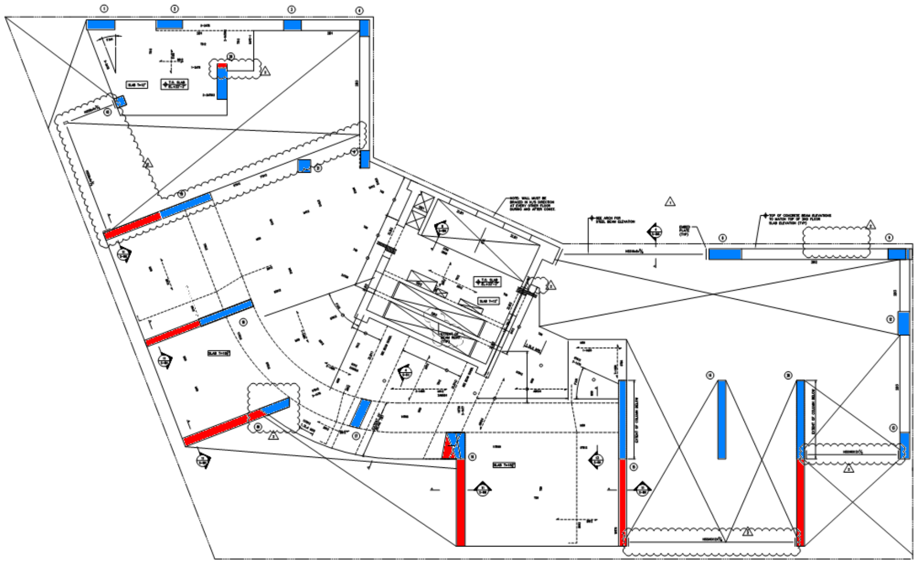


Figure 13: 2nd Floor column layout

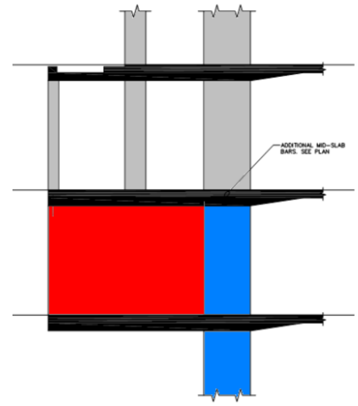


Figure 14: Cantilevered Column Elevation

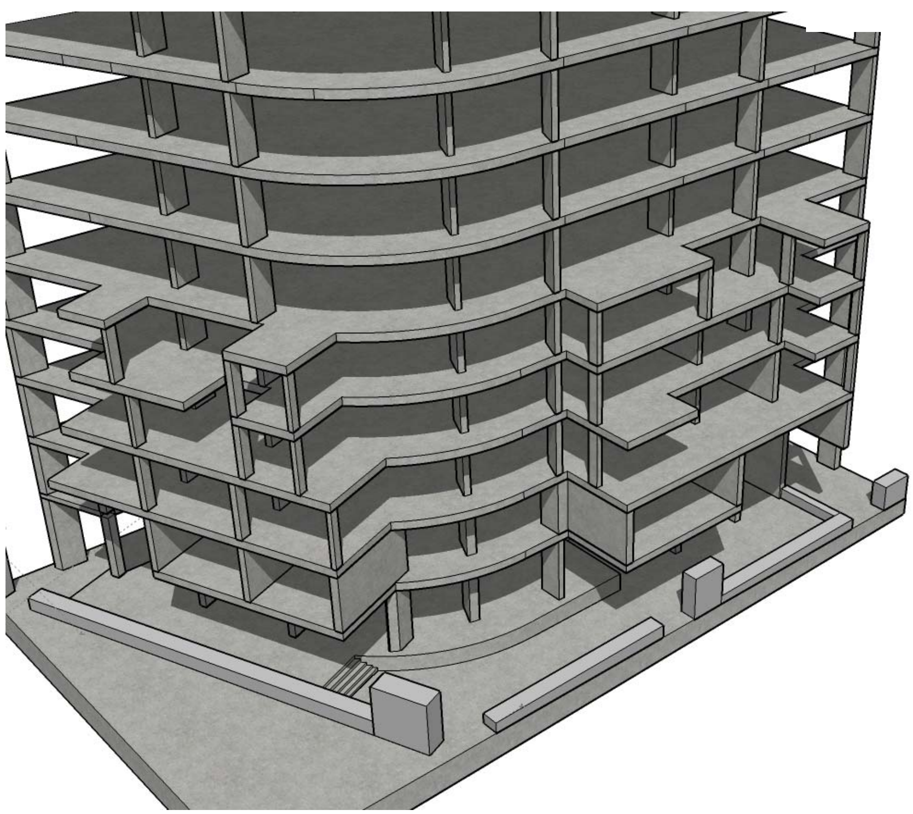


Figure 15: Model showing complicated balcony system

Lateral System

100 Eleventh Avenue's main lateral force resisting system is comprised of concrete shear walls located at the building elevator core, in combination with seven "long" columns, as shown in Figure 16 below. Because architectural constraints restricted the use of shear walls to the relatively small elevator core, the seismic loading necessitated that these seven columns also be designed to resist lateral forces. Two of these columns are connected to the main core via in-slab outrigger beams for additional stiffness. These 4' wide beams are reinforced with 11 #7 bars on both the top and bottom. The diaphragm connects the remaining columns to the building core. As lateral force is imposed on the building, the rigid floor distributes the forces to both the columns and shear walls, which in turn transfer the loads to the ground. The shear walls are typically 12" thick with #11 @12" E.F. vertically (Grade 75) and #6 @9" E.F. horizontally.

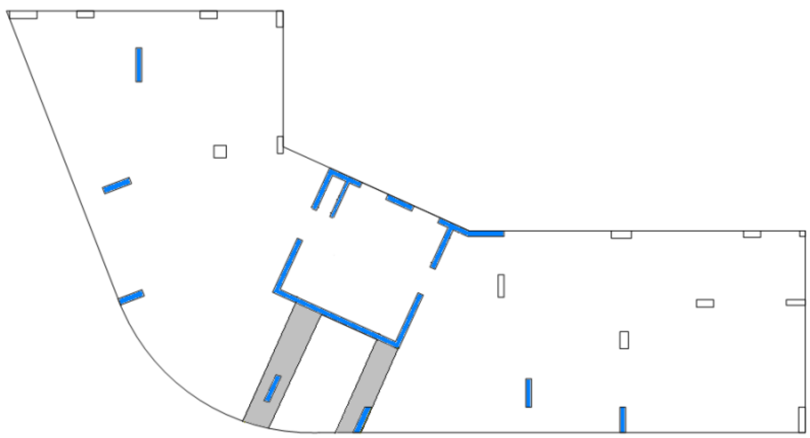


Figure 16: Lateral system with link beams denoted

Problem Statement

The floor system of 100 Eleventh Avenue must be designed to resist gravity forces due to live load, superimposed dead loads such as partitions and mechanical equipment, and the self weight of the structure. A reinforced 9"-thick concrete slab is sufficient throughout the majority of each level, where typical clear spans range from 18' to 23'. On the street-facing perimeter, however, the concrete slab must span lengths of up to 34', while supporting an additional 500 plf load from the panelized facade system. On top of this, the two-way floor system is weaker along its edge due to the lack of stiffening edge beams. To accommodate this, the slab thickens from 9" to 18.5" at the perimeter. This solution provides for a practical means of strengthening the slab along the perimeter, yet has several negative effects as well, such as increased weight and material. The interior architecture is also affected, with decreased floor-to-ceiling heights at the building perimeter and an unappealing appearance (partially compensated for by gradually increasing the slab thickness over a distance of 5' rather than undergoing an abrupt increase). On the lower six levels, the thickened slab along the perimeter intermittently extends outwards towards the second street facade, as can be seen in Figure 15 and in floor plans found in the Appendix, creating the balcony system that defines the lower levels. Several of these protrusions require the slab to cantilever, necessitating the use of post-tensioned high-strength steel Dywidag bars to control deflections caused by heavy facade and tree loads.

Additionally, on the 19th level a 13 foot offset on the building's east side requires the relocation of several columns from the 19th to 18th level. The gravity loads carried by the terminated columns on the 19th level must be transferred to the columns on the level below. Much like at the perimeter, the slab at this portion of the building is thickened to 18.5" in order to transfer these forces. In addition to an increased thickness, this transfer slab is heavily reinforced, with #10 @ 6" each way on both top and bottom of slab.

Figure 17: View of transition from 9" slab to 18.5" slab

Figure 18: Cantilevered slab as part of balcony system

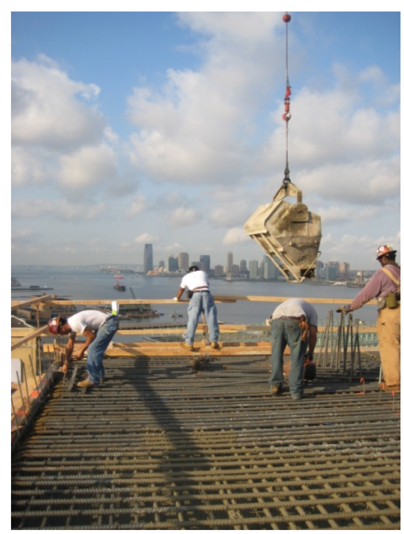


Figure 19: Heavily-reinforced 19th floor transfer slab

Proposed Solution

Post-tensioning the slab perimeter in one direction will be investigated as an alternative to the existing solution as a means of resisting the increased loads and spans found at the building perimeter. Based on results from Technical Report #2, the use of 17 1/2" ø tendons, with additional mild-steel reinforcing, allows the slab thickness to be reduced from 18.5" to 10". Further design concepts will be explored with the ultimate goal of reducing the slab thickness at the perimeter to the 9" used throughout the rest of the floor. The portions of the perimeter slab that extend outwards as part of the balcony system will be analyzed to ensure that the thinned slab, in combination with the existing post-tensioned Dywidag bars, will still provide sufficient strength and deflection control.

On the 19th floor, an alternative transfer system composed of post-tensioned beams will be used in lieu of the heavy transfer slab. To preserve floor-to-ceiling heights, the maximum depth of these beams will be the existing slab thickness of 18.5". See Figure 20 for a schematic sketch showing potential orientations of transfer beams. Because the columns do not lie in a grid, any orientation of a beam supported by two columns will likely have significant torsional forces that will need to be designed for.

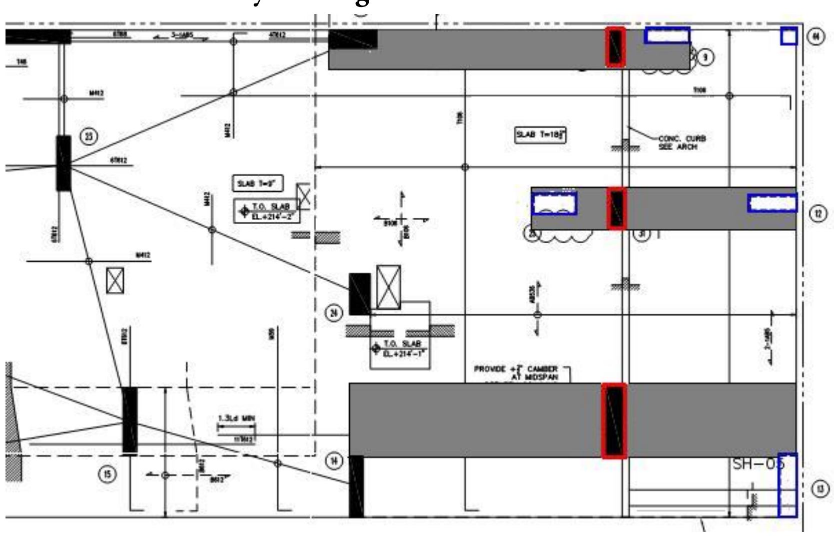


Figure 20: Schematic beam layout on 19th Floor with red denoting terminated columns and blue denoting new column locations on 18th level below

The redesign of the slab perimeter/balcony as well as the 19th floor column transfer system will be compared to the existing design using criteria such as material and labor savings, weight, improvements to interior space, and feasibility. In addition, any effects on the structure's foundations will be explored.

Solution Method

In order to redesign 100 Eleventh Avenue's slab edge, the acting gravity loads must be accurately determined from ASCE 7-05 and IBC 2006. In addition, a 500 lb/ft load on the slab edge from the facade will be assumed, as was with the existing design. To ensure full understanding of the existing design, the floor will be analyzed using RAM Concept, a computer program that utilizes the finite element method for concrete floor systems. RAM Concept requires the user to define design strips which link finite element analysis with the concrete code rules (ACI 318-02). Post-tensioning concepts will then be reviewed and preliminary slab thickness and tendon layout determined by hand, treating the slab perimeter as an equivalent frame using ACI 318-08 recommendations. Post-tensioning resources from the Portland Concrete Association will also be utilized. The preliminary post-tensioned tendons will then be entered into RAM Concept, allowing the program to generate the required slab thickness and mild-steel reinforcement, based on ACI 318-02. RAM Concept will also be utilized to verify the cantilevered slabs making up the balcony are sufficiently strong and stiff with the existing post-tensioned Dywidag bars.

The determined gravity loads will also be used in column load takedowns necessary for the 19th floor transfer system redesign. Potential locations for the transfer beams will be determined based on the column layout of the 19th and 18th floors. Preliminary hand calculations will be performed treating the system as beams supported by the 18th floor columns, with point loads from the 19th floor columns. The depth of the post-tensioned beams will be kept as minimal as possible, with a maximum of 18.5" in order to preserve the existing floor-to-ceiling height. These sizes will then be verified and/or redesigned using RAM Concept, modeling it much like a one-way slab. Only the 18.5"-thick portion of this floor will be analyzed.

Breadth Topics

The impact of the redesign of the structure's slab edge and 19th level transfer system is not entirely encompassed by material savings, weight, and appearances. Any modification to the structural system will also, in turn, affect the construction of 100 Eleventh Avenue. Thus, a construction management breadth will be studied. More specifically, this study will focus on the impact the redesign will have on the construction process, such as scheduling, sequencing, and the area's familiarity with post-tensioning. The inclusion of beams on the 19th story will require a detailed look at the increased labor involved with the forming of the transfer members.

Another area outside of the structural system that will be studied is the day lighting and shading of 100 Eleventh Avenue. Because nearly half of the building's perimeter is clad in glass, managing the amount of natural light entering its spaces is an important issue. Currently, Lutron solar shades and blackout shades are used in spaces adjacent to the panelized curtain wall, allowing occupants to vary the amount of penetrating sunlight with the touch of a button. Alternative systems will be looked at, with the hope of finding an efficient, more attractive option.

Figure 21: Interior of residential unit showing current shading devices

Task and Tools

Post-tensioned Slab Perimeter

Task 1: Accurately determine gravity loads acting on floor

- **a) Dead and live loads, as well as load factors, from ASCE 7-05 & IBC 2006**
- **b) 500 lb/ft curtain wall**

Task 2: Analyze existing system to ensure full understanding and to determine precisely where the 9" slab becomes insufficient

- **a) Become familiar with RAM Concept**
- **b) Model existing system in RAM Concept**

Task 3: Preliminary post-tensioned design and tendon layout

- **a) Review PT concepts**
  - **i) ACI 318-08**
  - **ii) PCA resources**
  - **iii) Class notes**
- **b) Perform preliminary hand calculations**

Task 4: Design using RAM Concept

- **a) Develop computer model**
- **b) Design post-tensioning**
- **c) Compare to hand-calculated results**

Task 5: Consider balcony system on lower 6th floors

- **a) Include in computer model**
- **b) Confirm thinned slab is sufficient**
- **c) Verify with hand calculations**

19th Floor Transfer System

Task 6: Column load takedown

Task 7: Analyze existing system to ensure full understanding

- **a) Model existing system in RAM Concept**
- **b) Verify with hand calculations**

Task 8: Preliminary sizing of post-tensioned beams by hand

Task 9: Design using RAM Concept

Task 10: Compare cost, material, weight, and interior appearance to existing design

Task 11: Analyze effect on foundations

Breadth Studies

Task 12: Construction Management Impacts

- **a) Determine time required to construct existing and modified floor system**
  - **i) Research typical floor construction cycles**
  - **ii) Research NYC floor construction cycles**
  - **iii) Research NYC contractors' familiarity with post-tensioning**
- **b) Analyze impact of additional formwork at 19^{th} story**
  - **i) Research efficient forming procedures**
- **c) Compare**

Task 13: Shading Study

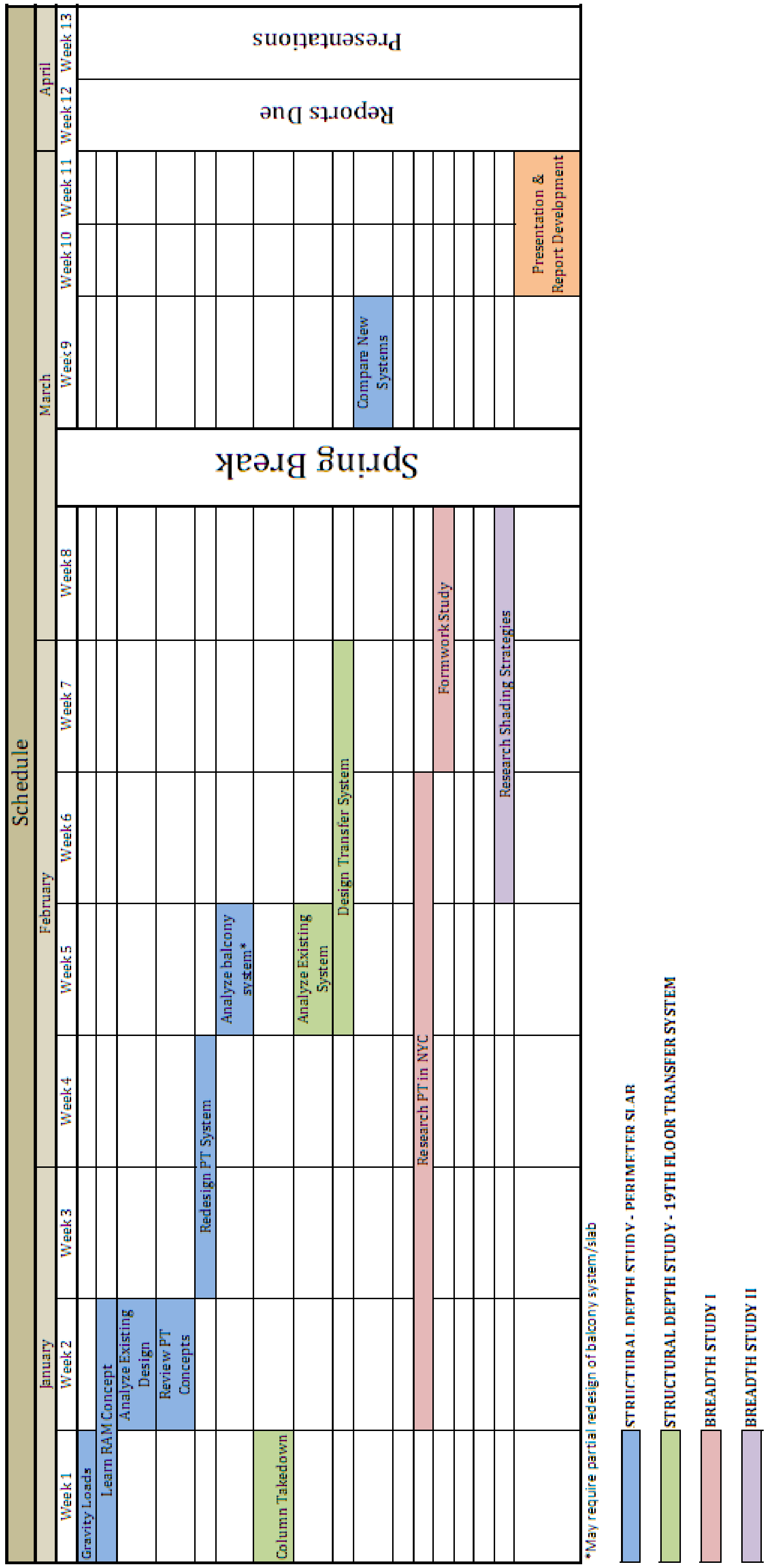
- **a) Attain additional information on existing shading system**
- **b) Research alternative shading devices**
- **c) Compare using criteria such as cost, practicality, and appearance**

Presentation

Task 14: Prepare presentation

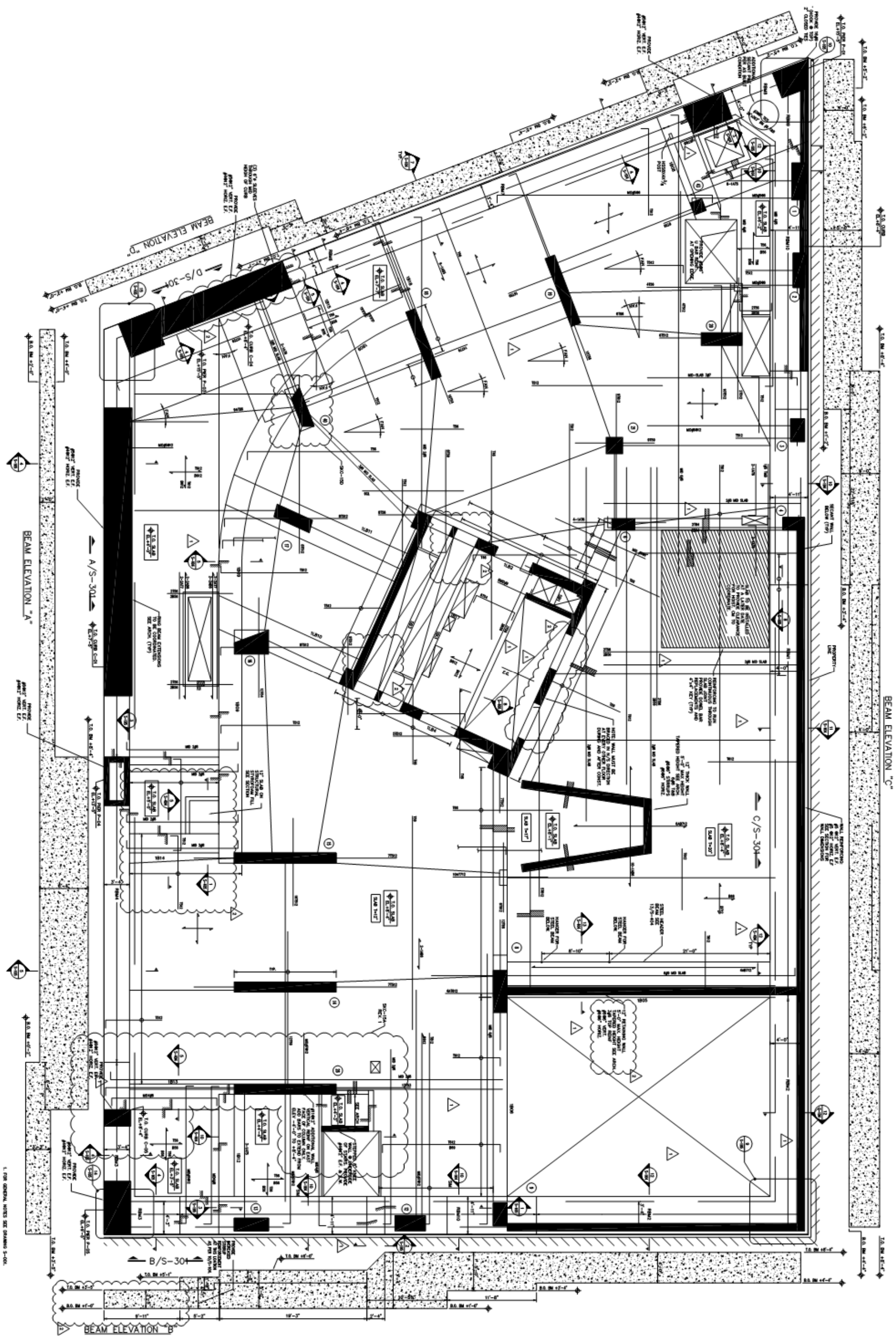
- **a) Final Report**
- **b) PowerPoint**
- **c) Miscellaneous**

Timetable

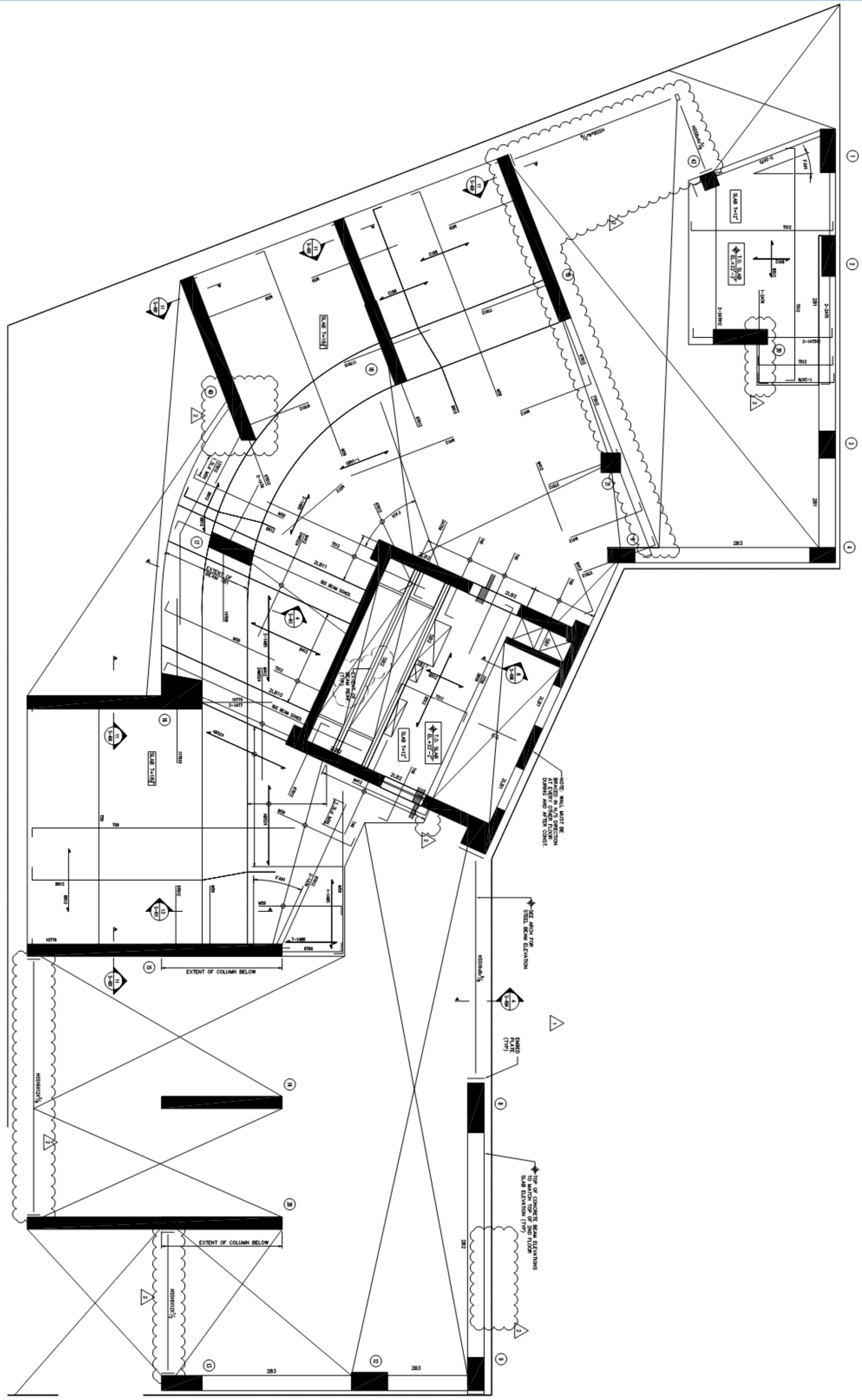

Schedule
January
February
March
April
Week 1
Week 2
Week 3
Week 4
Week 5
Week 6
Week 7
Week 8
Week 9
Week 10
Week 11
Week 12
Week 13
Gravity Loads
Learn RAM Concept
Analyze Existing Design
Review PT Concepts
Redesign PT System
Analyze balcony system*
Column Takedown
Analyze Existing System
Design Transfer System
Compare New Systems
Research PT in NYC
Formwork Study
Research Shading Strategies
Presentation & Report Development
Spring Break
Reports Due
Presentations
*May require partial redesign of balcony system/slab
STRUCTURAL DEPTH STUDY - PERIMETER SLAB
STRUCTURAL DEPTH STUDY - 19TH FLOOR TRANSFER SYSTEM
BREADTH STUDY I
BREADTH STUDY II

APPENDIX

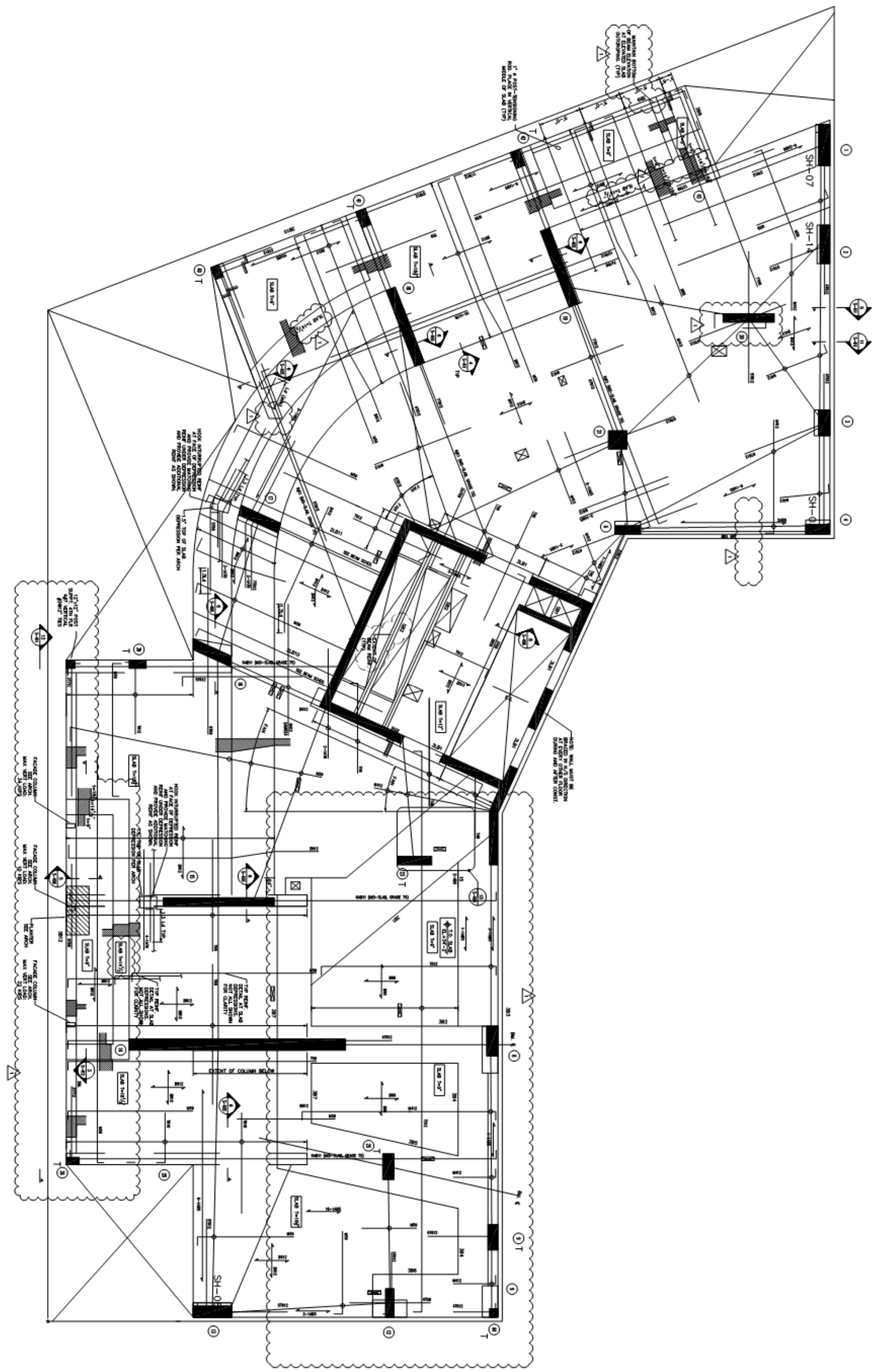
BUILDING PLANS



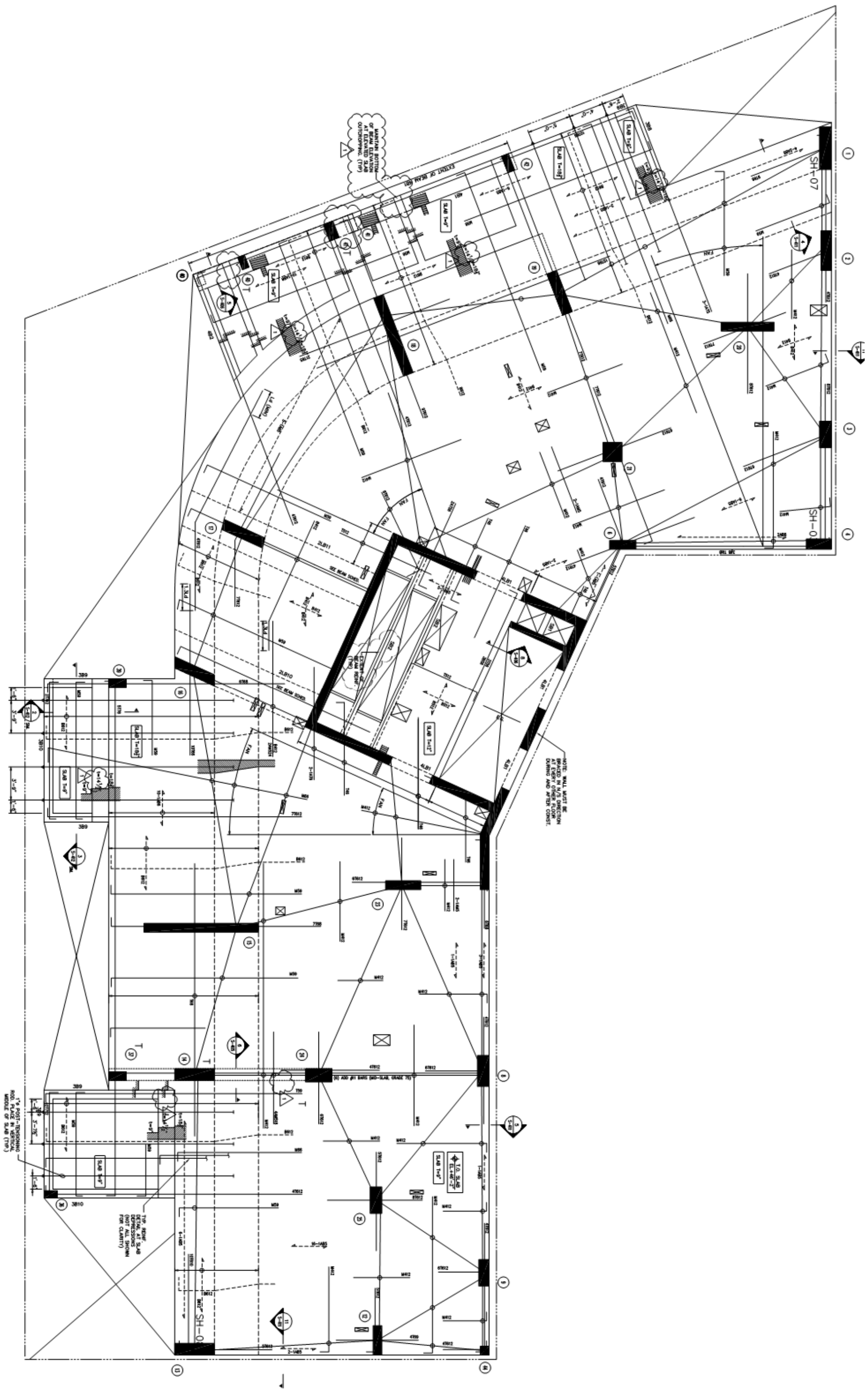
Ground Floor Plan



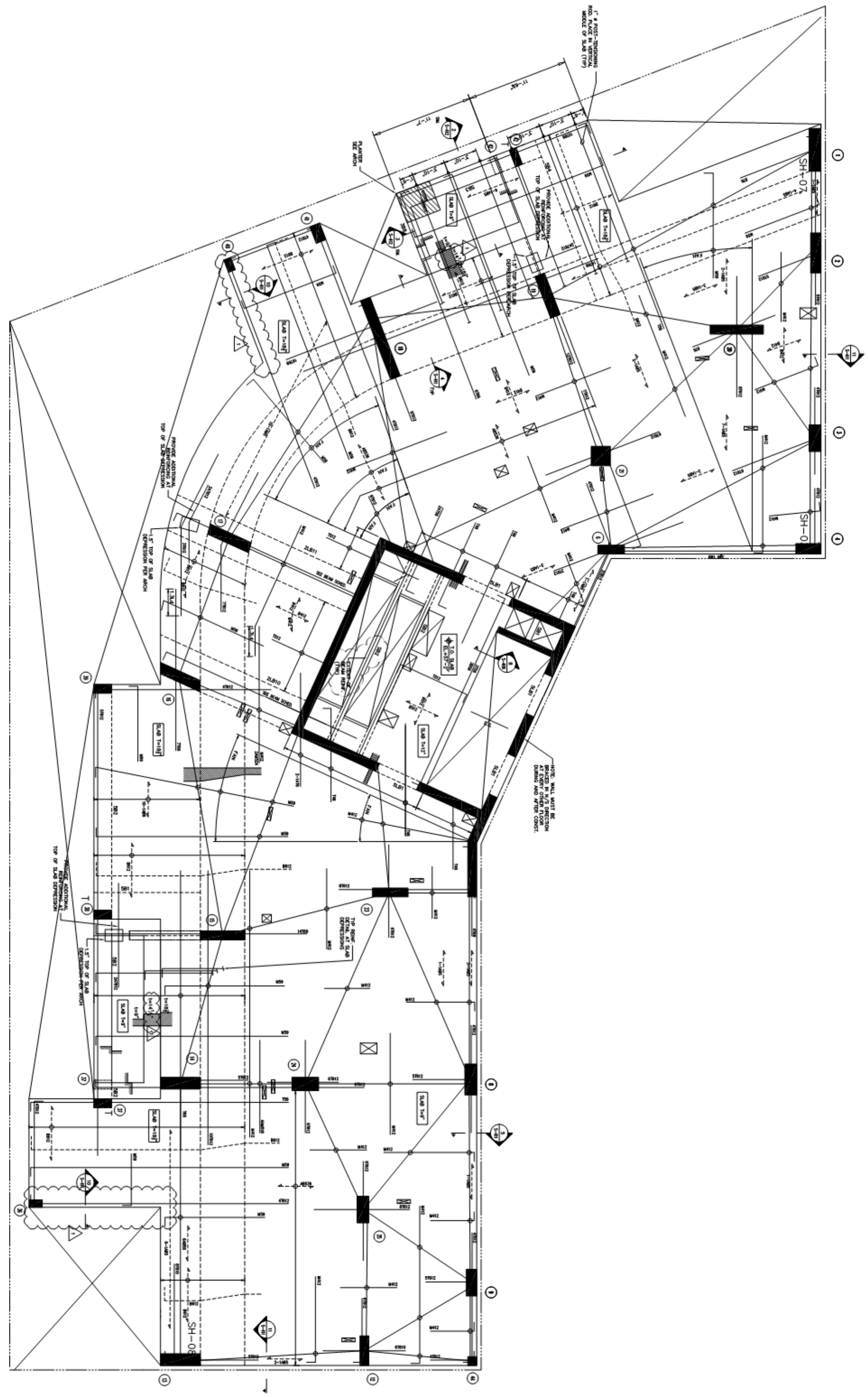
2nd Floor Plan



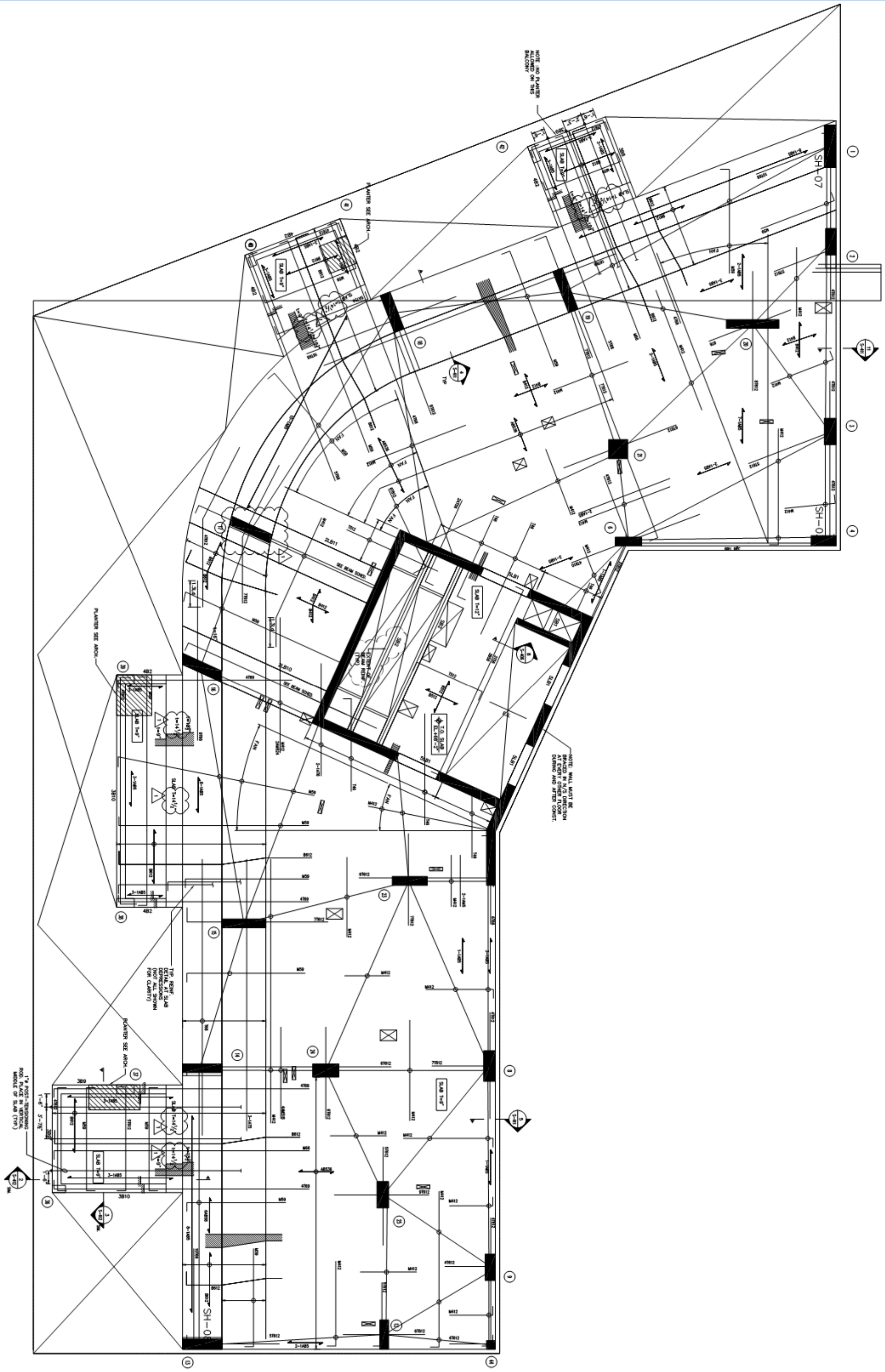
3rd Floor Plan



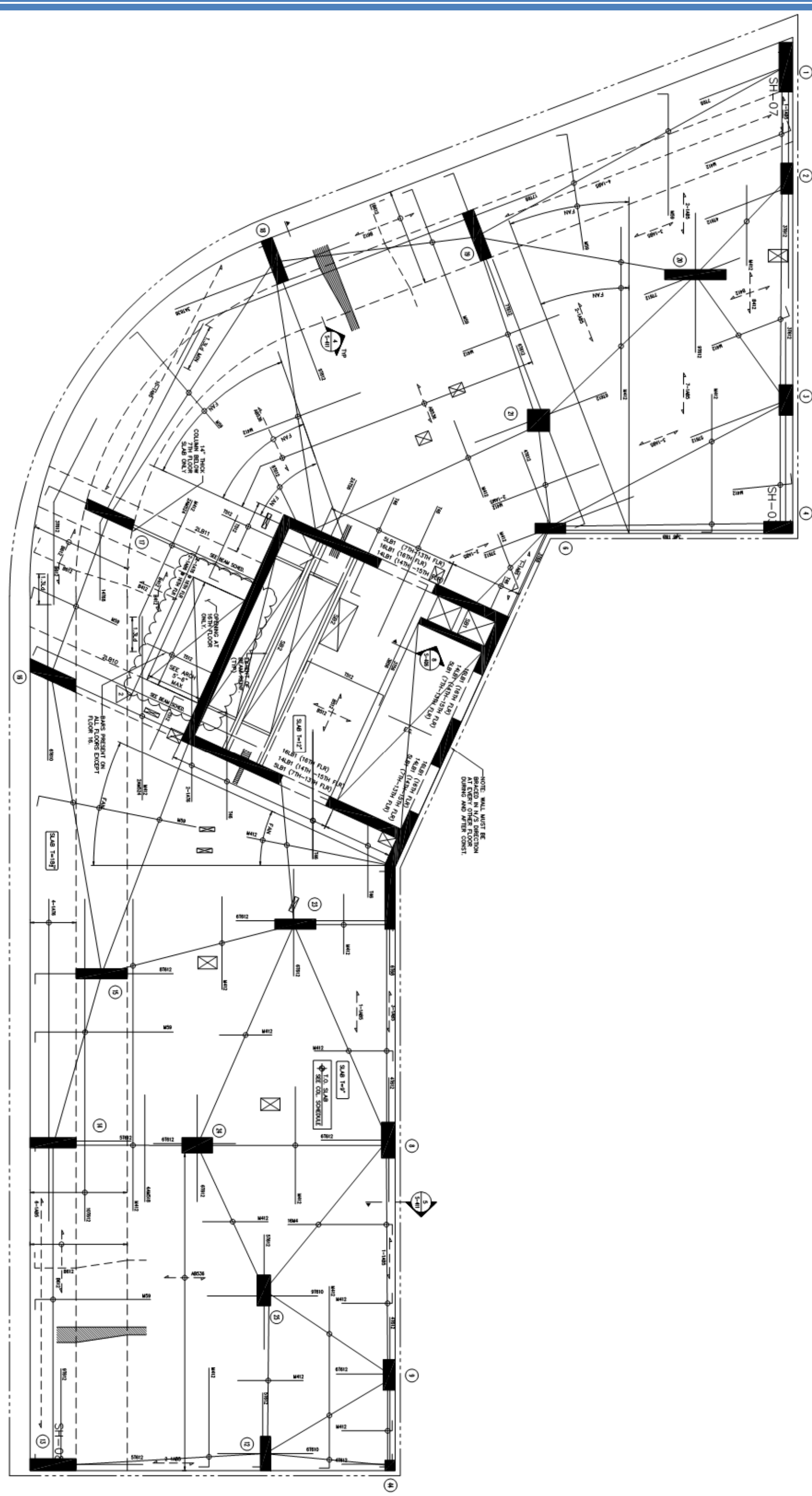
4th Floor Plan



5th Floor Plan



6th Floor Plan



7th-16th Floor Plan
17th-Roof Plans differ from typical plan only slightly