Image Courtesy of Cannon Design

The New Library at the University of Virginia's College at Wise

Macenzie Ceglar | Structural Option

Advisor : Heather Sustersic

April 14, 2014

Image Courtesy of Cannon Design

UVA's New Library

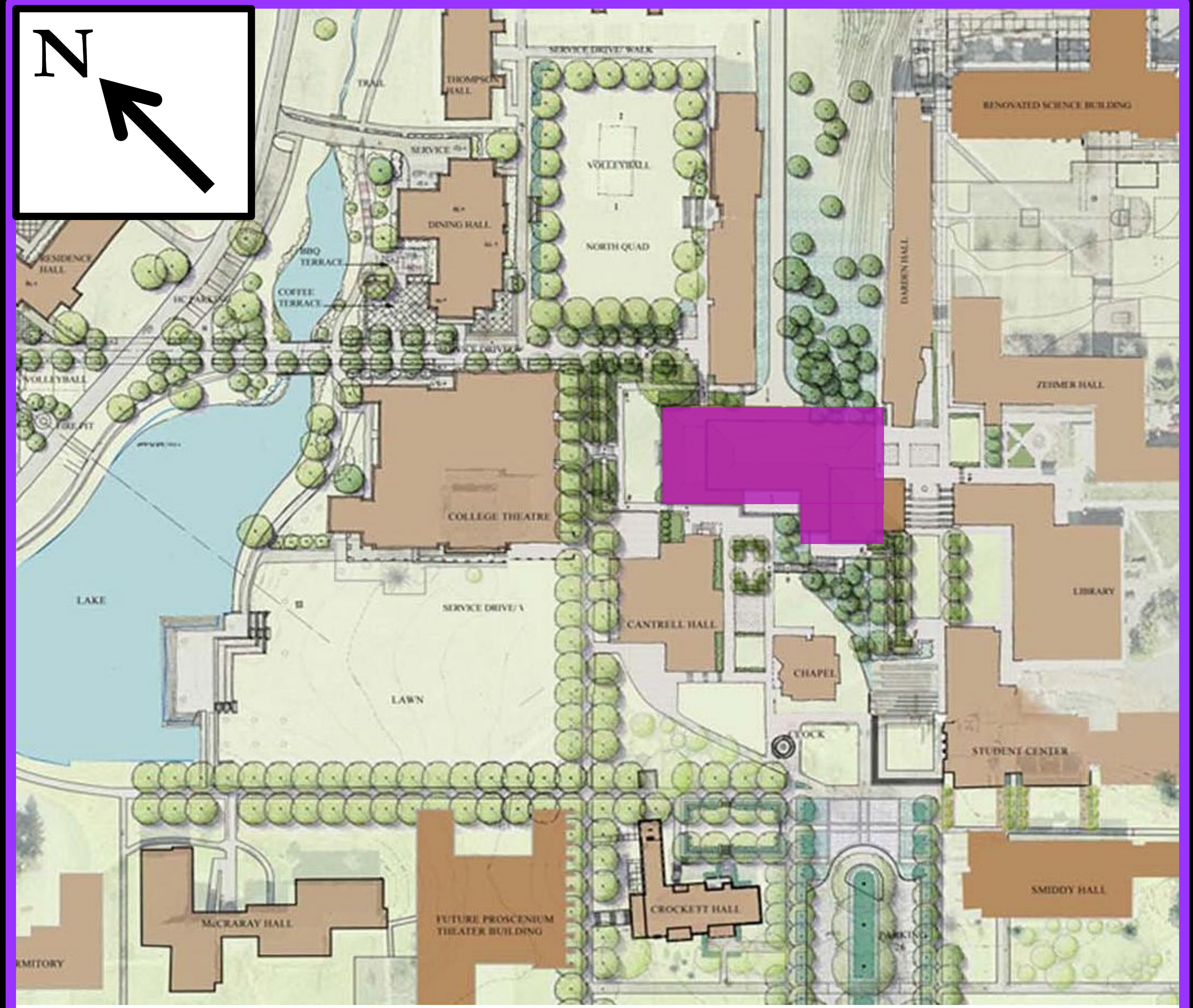
- **Building Introduction**
  - Statistics
  - Gravity System
  - Lateral System
- Problem Statement & Solution
- Two-way System
- PT System
- Lateral System
- Cost and Schedule Analysis
- System Comparison
- Conclusion

Building Introduction

Owner: University of Virginia
Architecture & Engineering: Cannon Design

Size: 68,000 GSF
Stories Above Grade: 6
Height: 102 FT
Cost: $43 Million

August 2012 – August 2015



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Building Introduction

Unique Feature: Integration into 60 Hill Side

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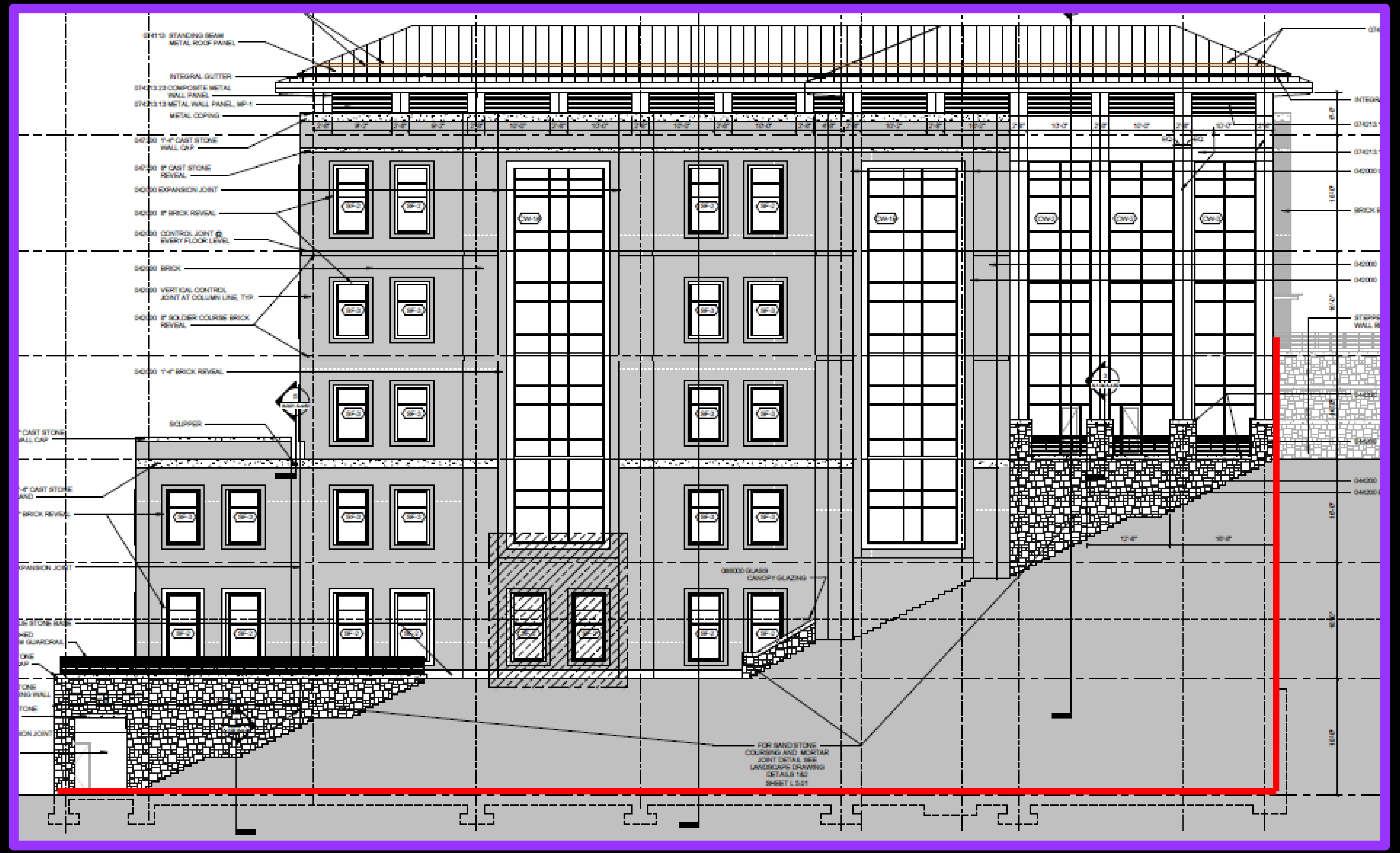

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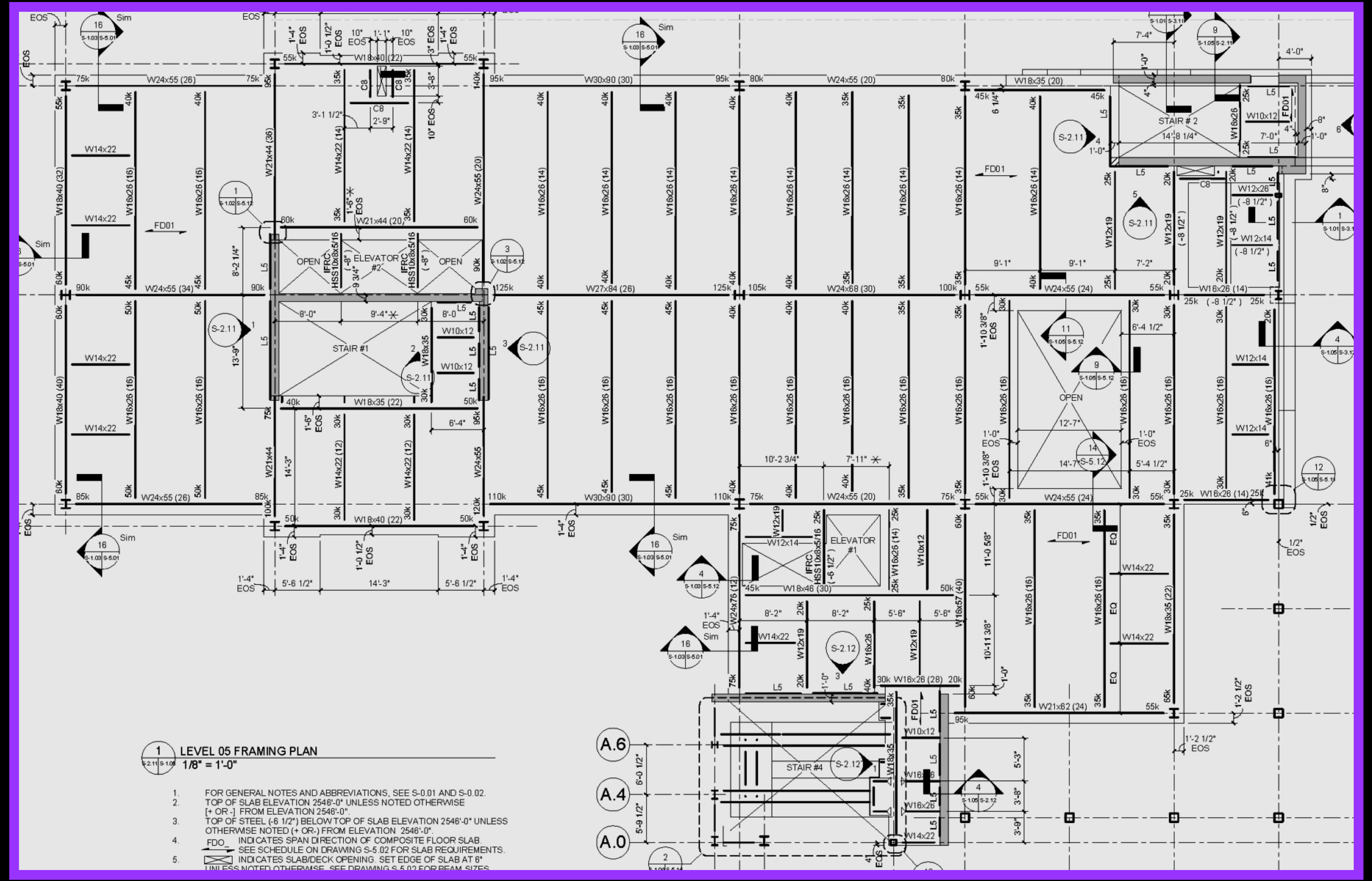
Existing Gravity System

- Spread/Strip Footings
- Temporary-Leave-In-Place Retaining Wall System

- Composite Steel Floor Framing
  - 2” 18 ga. Metal Decking
  - 4 ½” NWC Topping
  - 3 ½” x ¾” Studs

- Wide Flange Members

- Typical Bay Size: 25’-4” x 25’-4”



Images from Construction Documents

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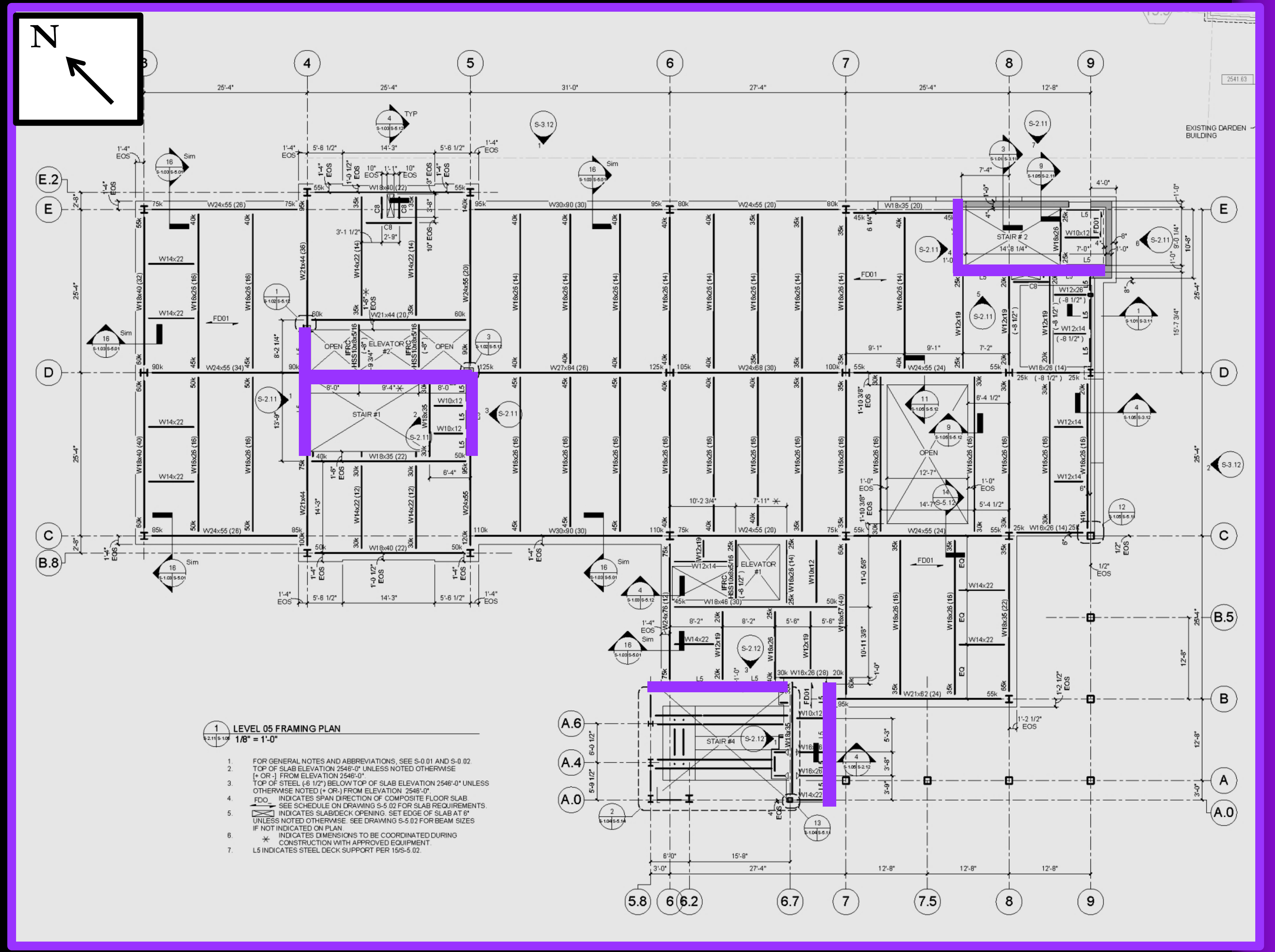
Existing Lateral System

- Ordinary reinforced concrete shear walls
  - 12" thick
  - #5 rebar @ 18" EW EF
- Located near stairs and elevator shafts



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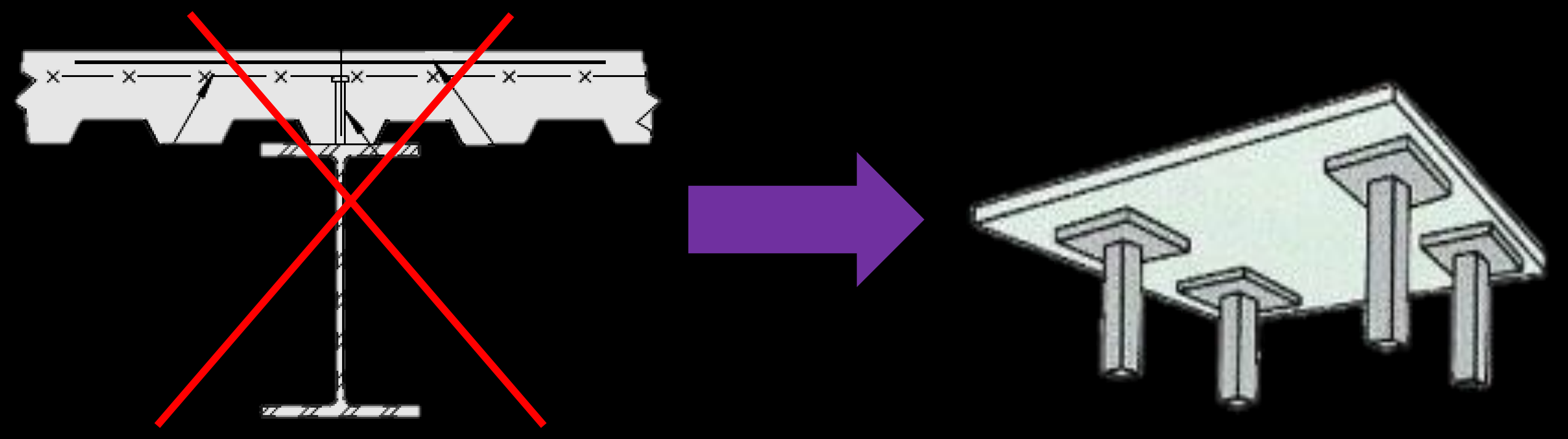
Problem Statement

- Exiting structure well designed
- Problem Scenario
  - Redesign the structure in <u>concrete</u>



Proposed Solution

- Redesign structural systems as a two-way concrete slab system
- Address deflections in longer span bays
- Investigate the possibility of a post-tensioned system
- Determine feasibility of a concrete system
  - Consider cost and schedule impact

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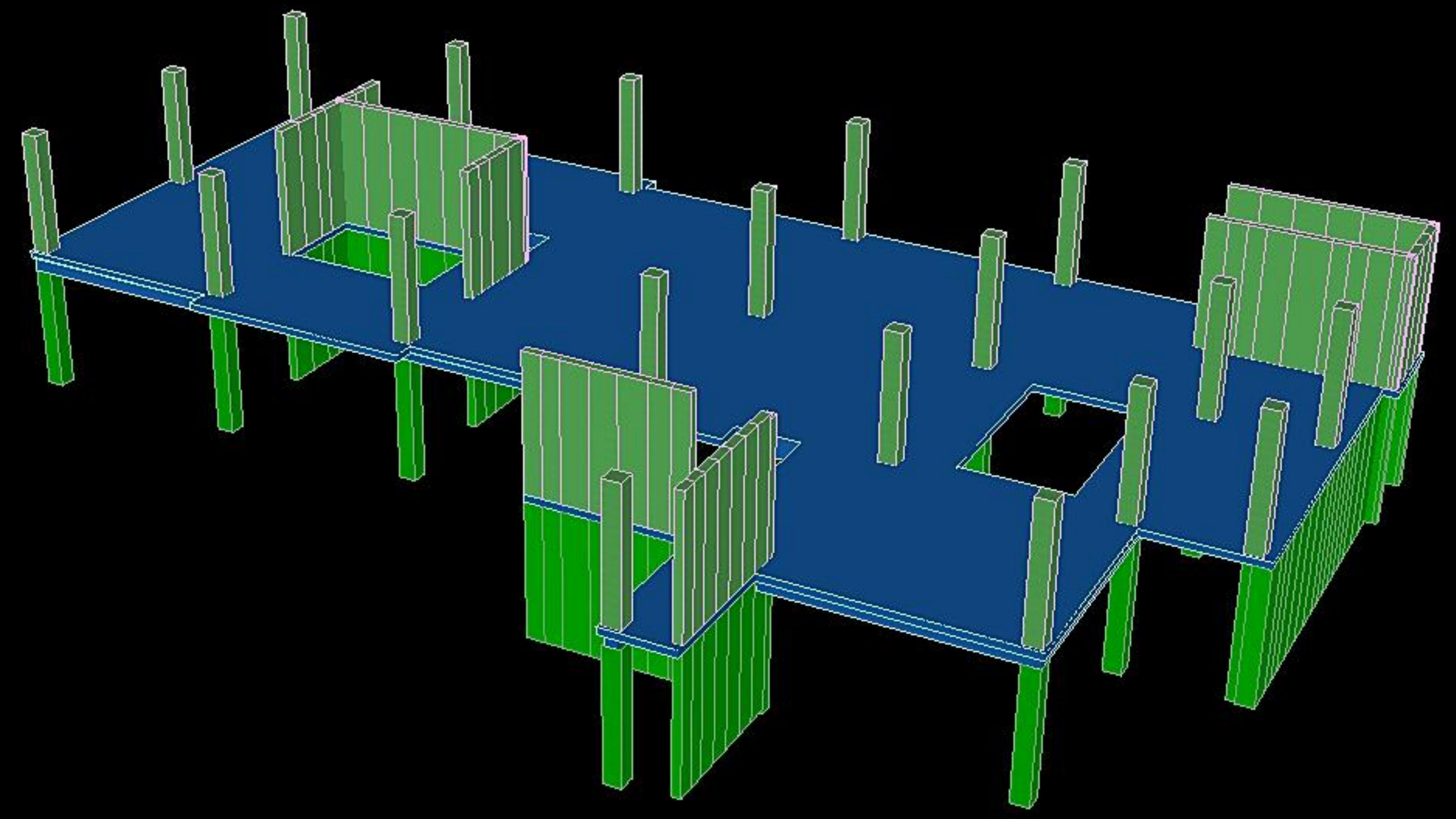
Two-Way Concrete System



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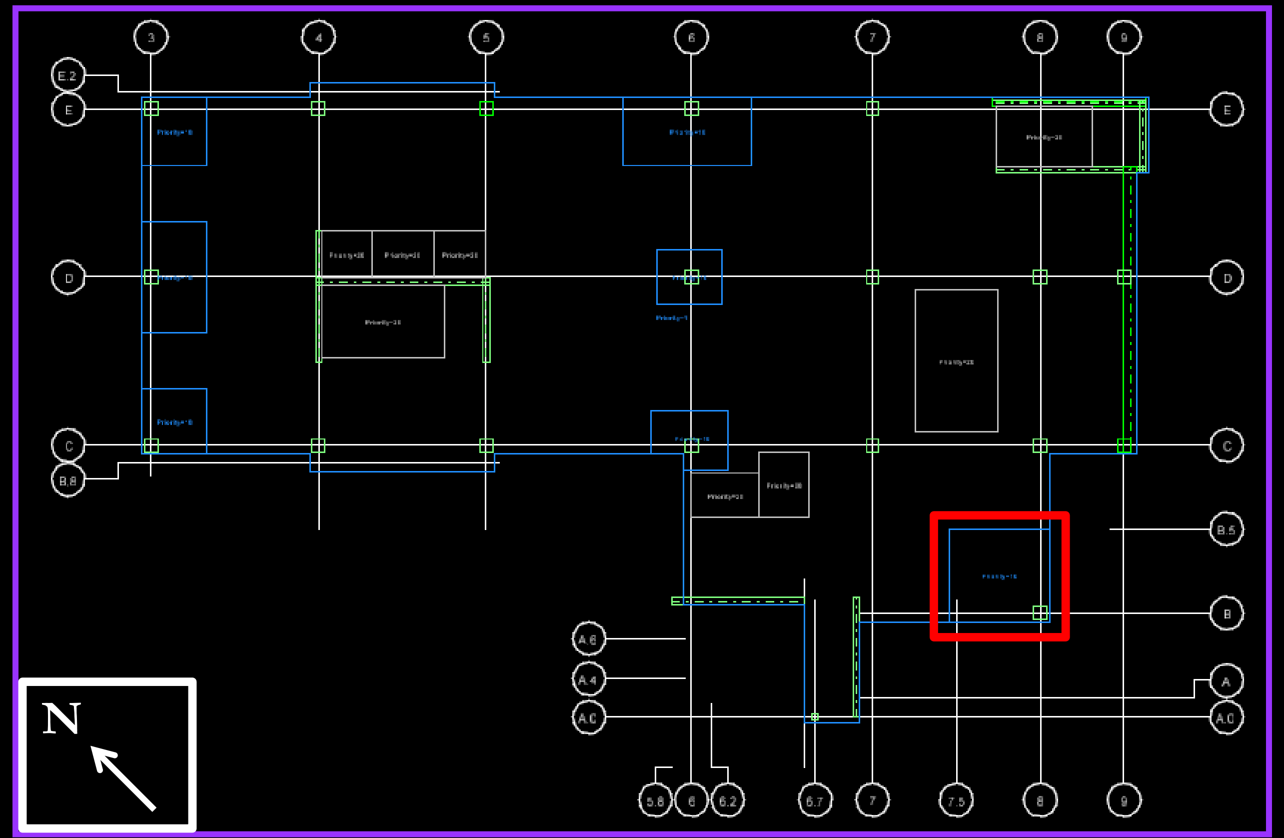
Floor Slab Design

- Trial slab thickness: 10"
- Drop Panel Sizes:
  - L/6 in each direction
  - Thickness: 1.25h =12.5"
- Punching shear controlled design



Column	-X (FT)	+X (FT)	-Y (FT)	+Y (FT)	Thickness (IN)	Required an Increase in Size
3E	1.33	8.44	8.44	1.33	6	Yes
3D	1.33	8.44	8.44	8.44	9	Yes
3C	1.33	8.44	1.33	8.44	9	Yes
6E	10.33	9.11	8.44	1.33	4	Yes
6D	5.17	4.56	4.22	4.22	6	No
6C	6.20	5.47	3.83	5.07	2.5	Yes
8B	13.67	1.33	1.33	12.67	13	Yes

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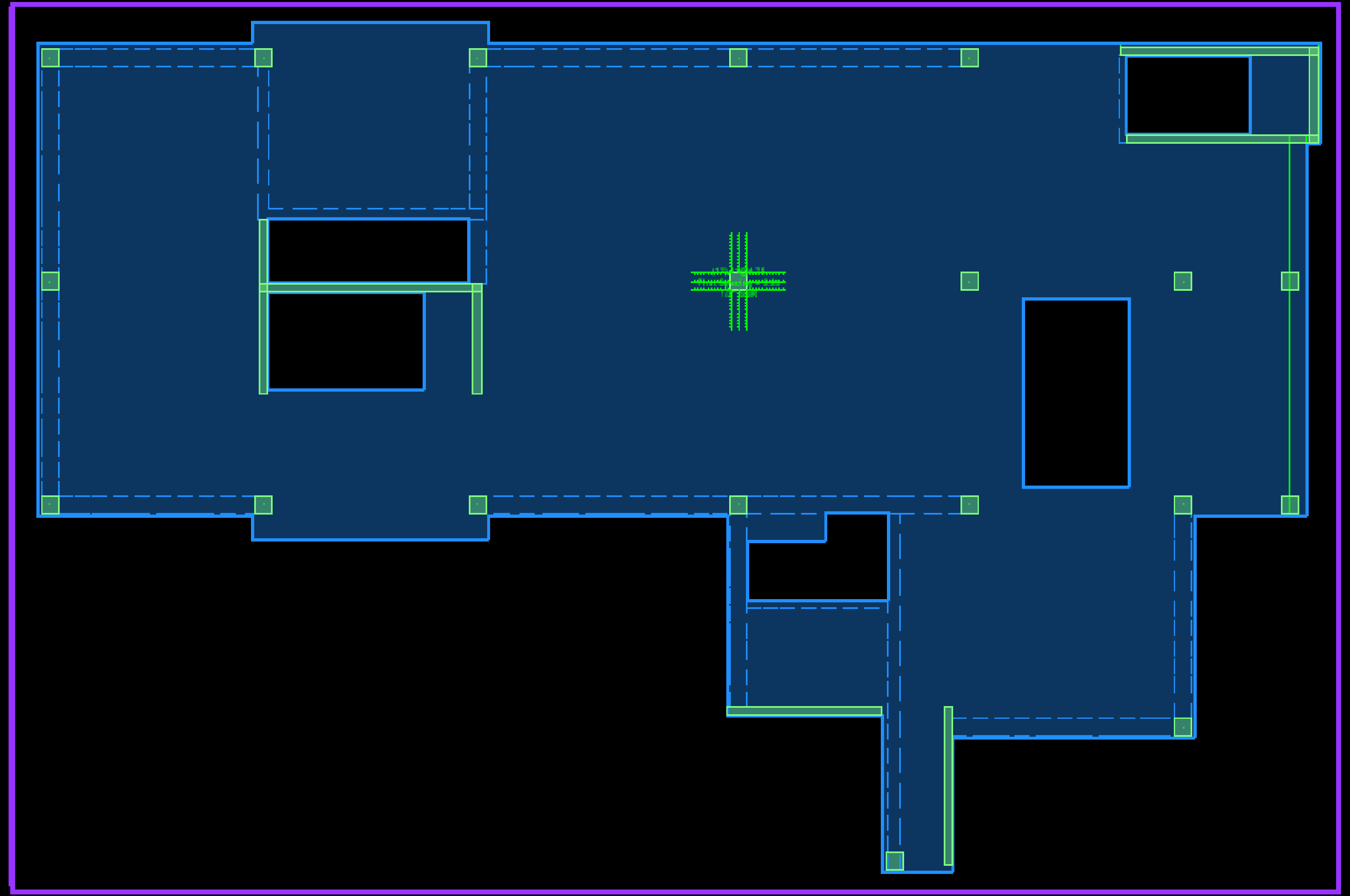
Trial Floor Slab Designs



Drop Panels Only

Shear Studrails

Drop Panels & Edge Beams

Shear Studrails & Edge Beams

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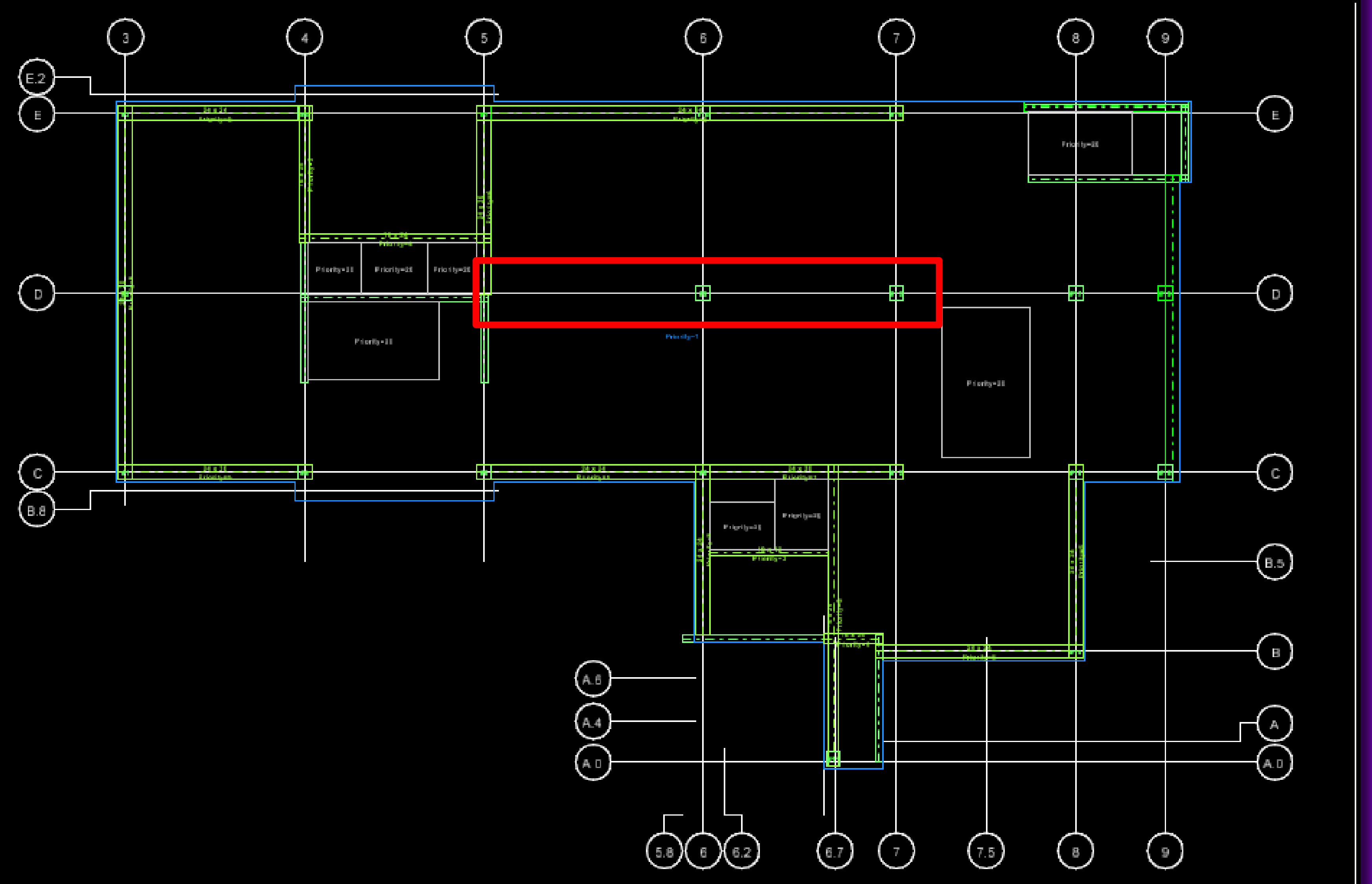
Deflections

- Maximum Allowable Deflection: L/480
- Initial Deflections:

Span	Length (FT)	Deflection	L/480	Pass/Fail
5D - 6D	31	1.33	0.775	Fail
6D - 7D	27.33	1.02	0.683	Fail
5E - 6D	40	1.43	1.0	Fail
6E - 7D	37.33	1.24	0.933	Fail
5C- 6D	40	1.33	1.0	Fail



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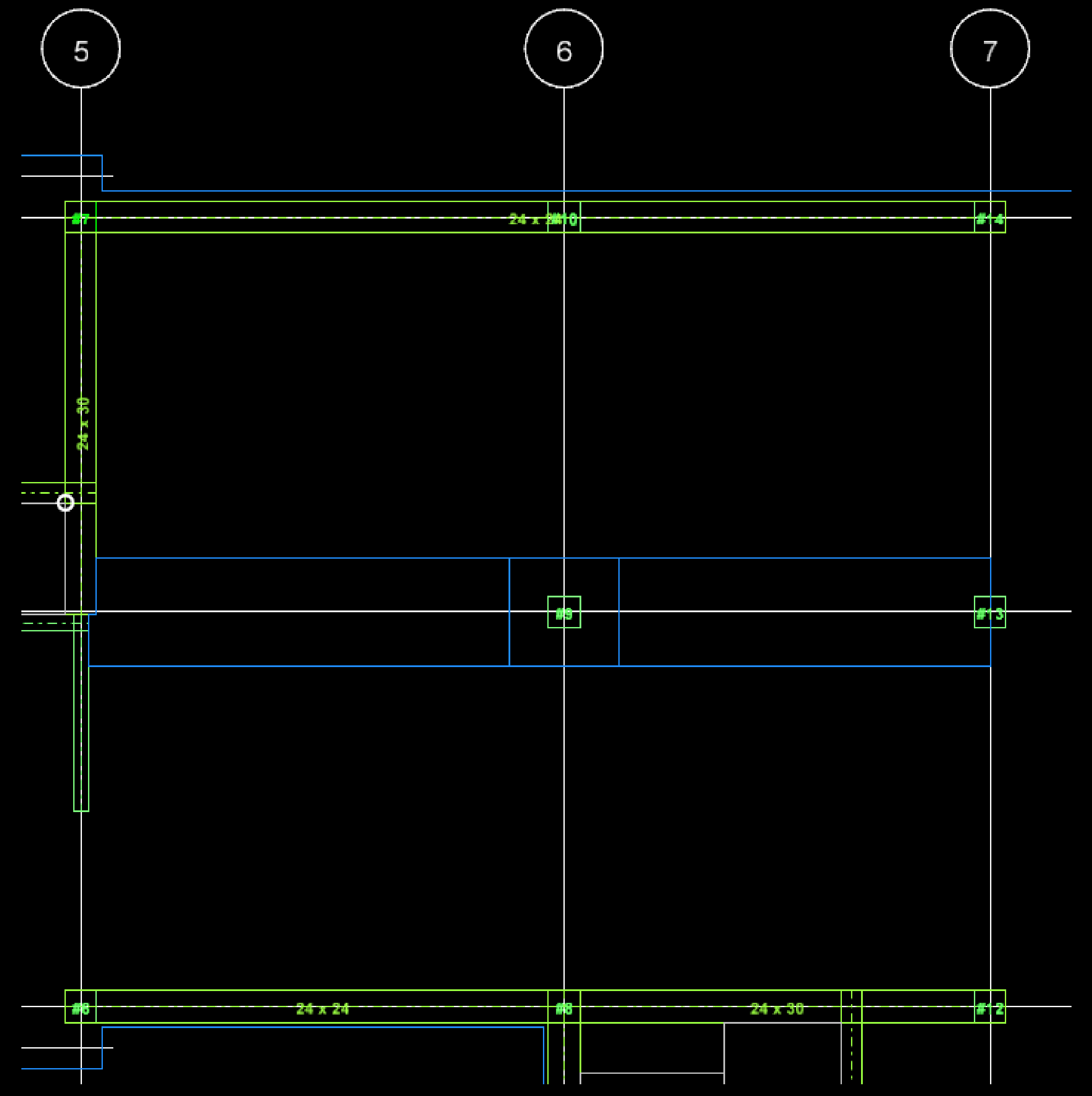
Deflections

- Trial Design Solutions:
  - Weighted Average
  - ~~Compression Reinforcement~~
  - Drop Panels
  - Shallow Beams

Span	Length (FT)	Deflection	L/480	Pass/Fail
5D - 6D	31	0.709	0.775	Pass
6D - 7D	27.33	0.511	0.683	Pass
5E - 6D	40	0.875	1.0	Pass
6E - 7D	37.33	0.817	0.933	Pass
5C- 6D	40	0.827	1.0	Pass



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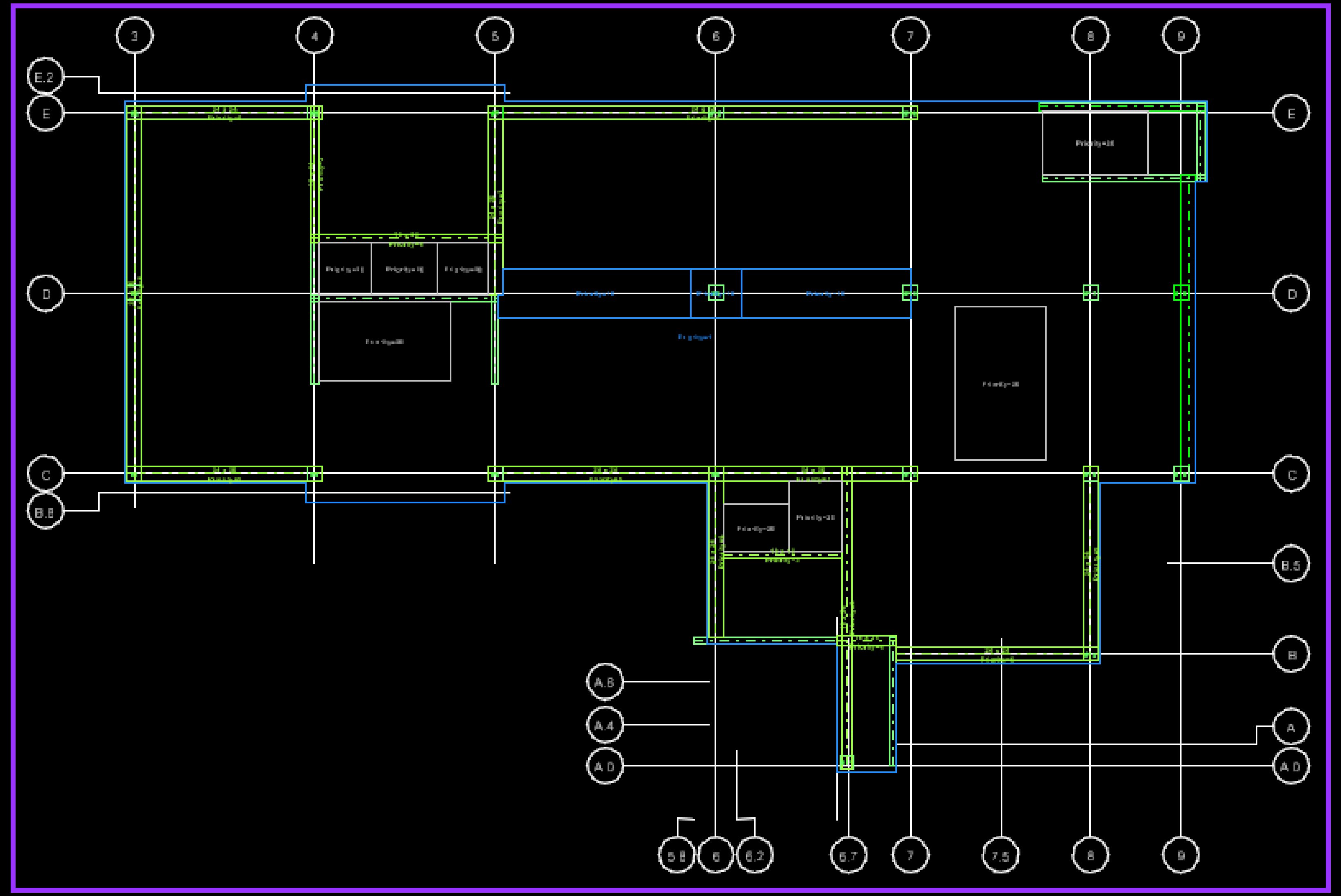
Final Floor Slab Design

- Slab thickness: 10"
- Drop Panel: 7' x 7' x 6"
- Shallow Beam: 7' x 14"
- Additional edge beams and interior beams
- Program output verified by hand



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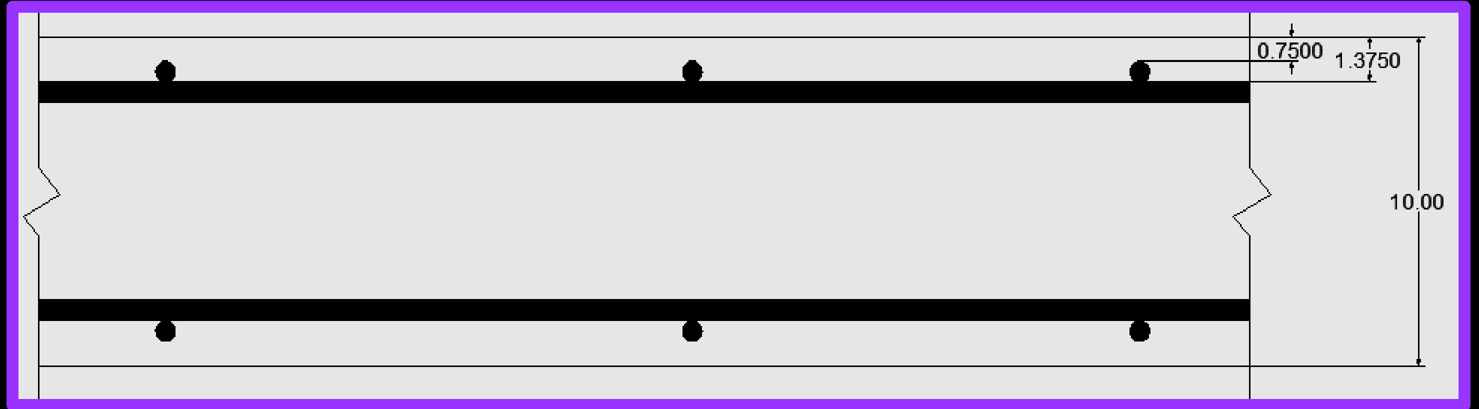
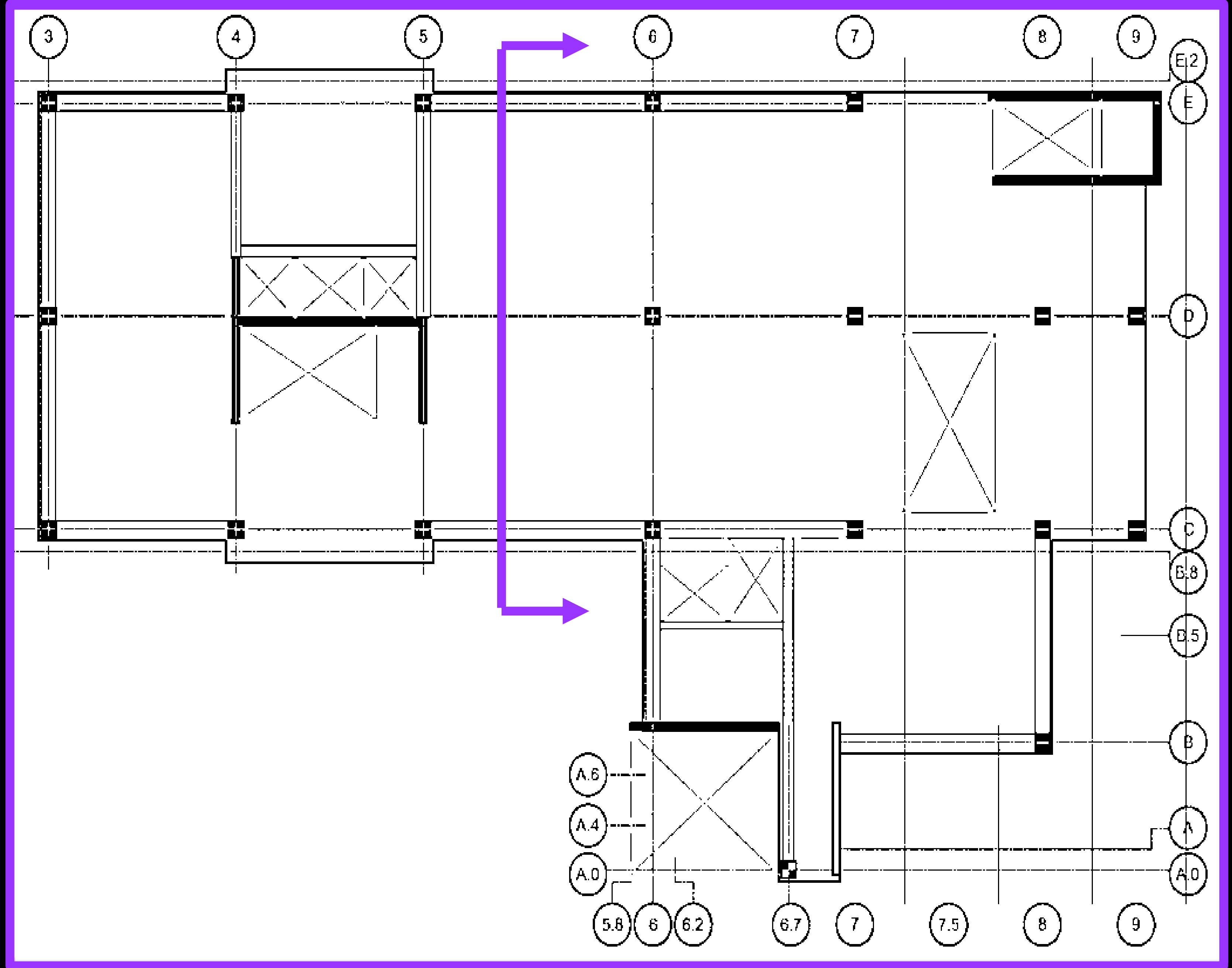
Slab Reinforcement

Typical Slab Reinforcing Schedule				
Slab Thickness	Top Mat		Bottom Mat	
	E-W	N-S	E-W	N-S
0'-10"	#5 @ 16"	#5 @ 16"	#5 @ 16"	#5 @ 16"





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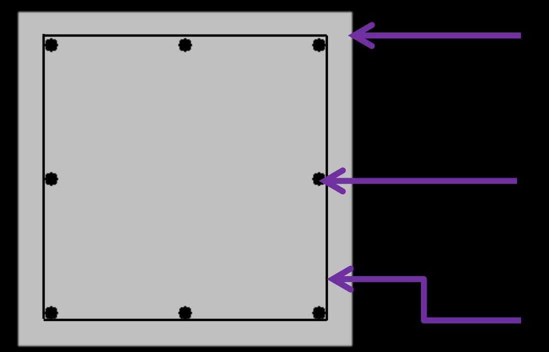
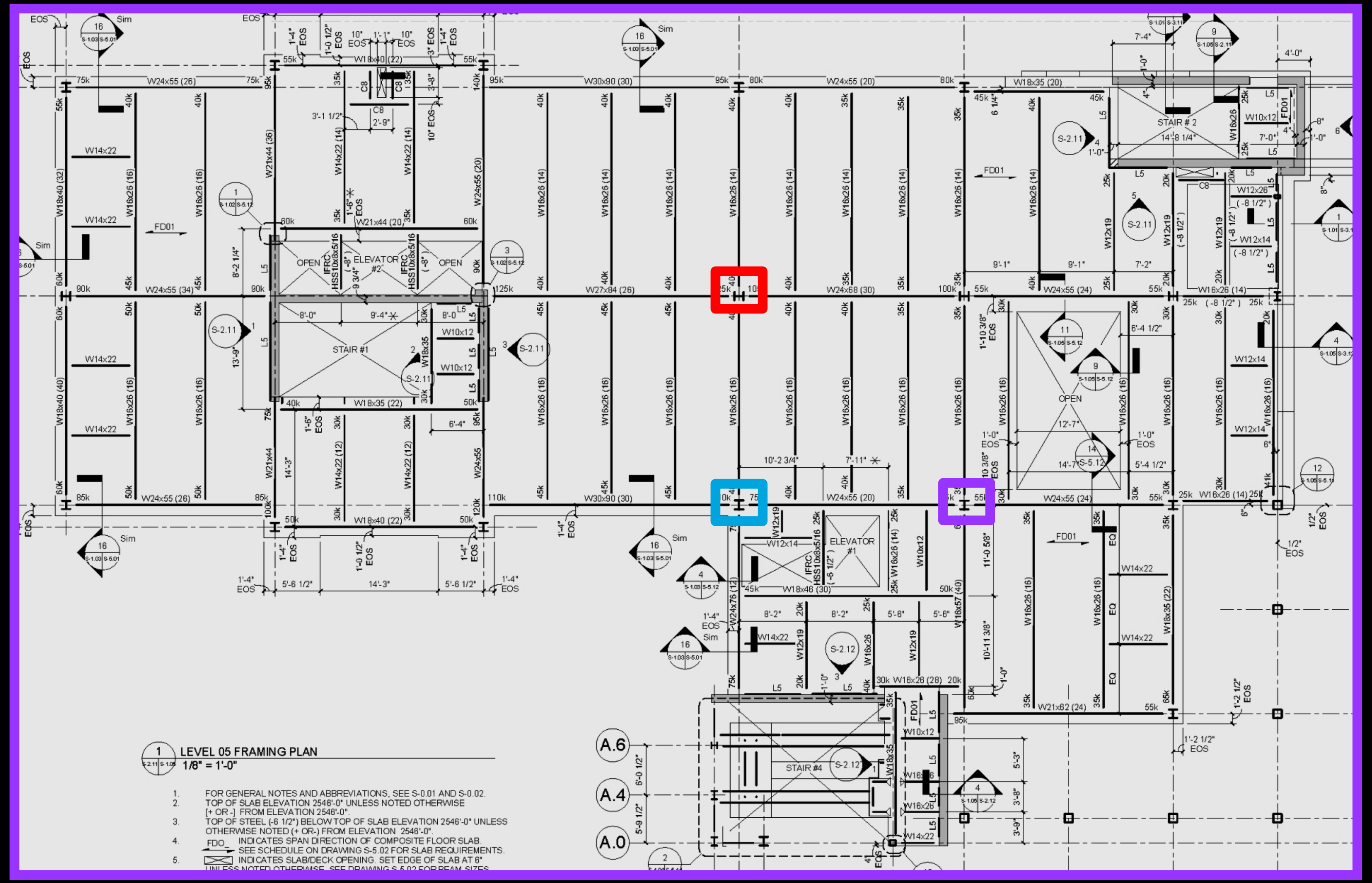
Column Redesign

- Typical:



- Non-Typical Columns:
  - 6D
  - 6C
  - 7C



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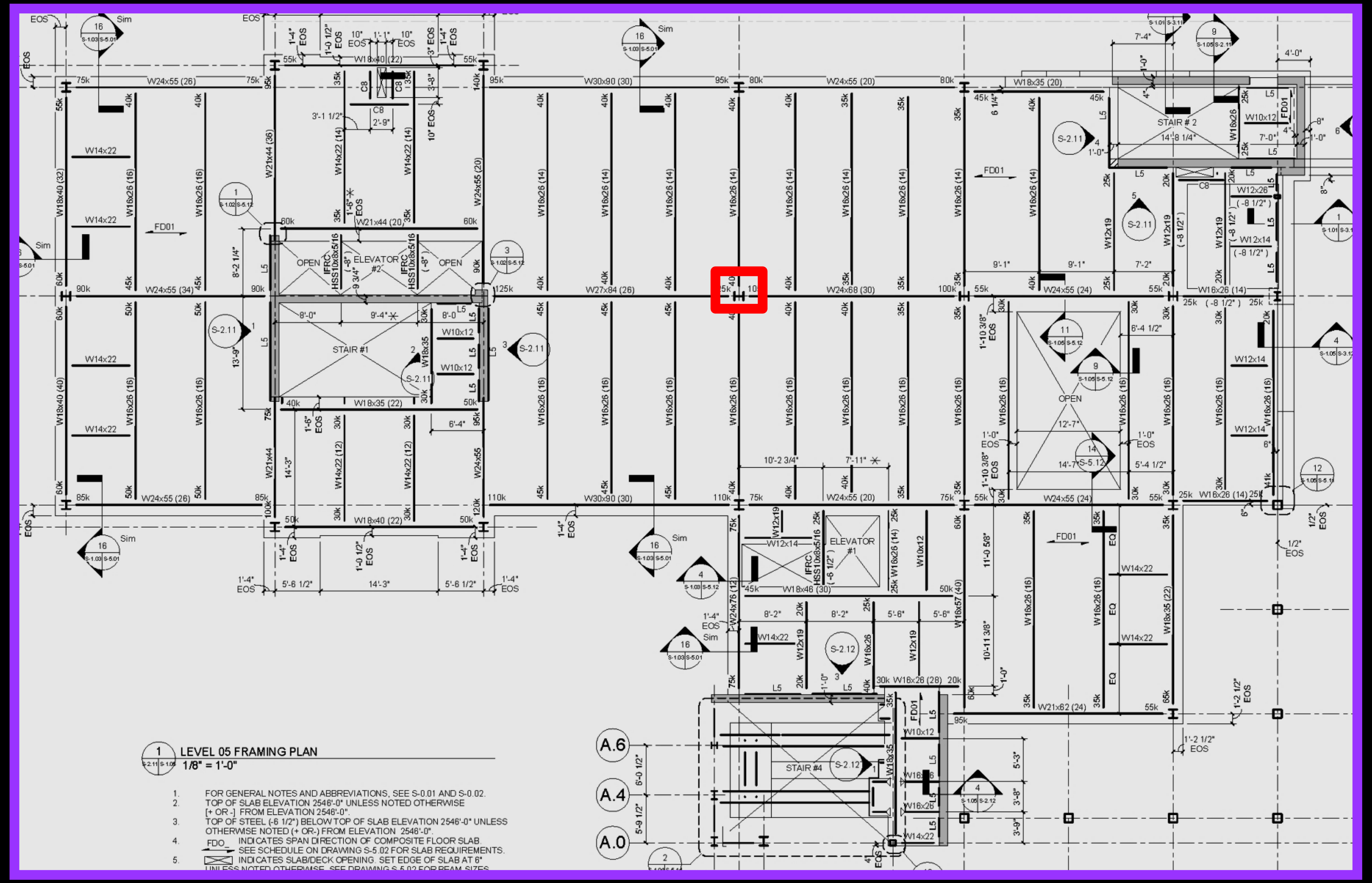
Column Redesign

Level	P_u (k)	øPn/Pu
6	185	6.5
5	495	2.4
4	803	1.5
3	1112	1.08
2	1420	1.24
1	1730	1.02

Levels 6–3:
- 24" x 24"
- (8) #8 Bars

Levels 2–1:
- 28" x 28"
- (16) #8 Bars



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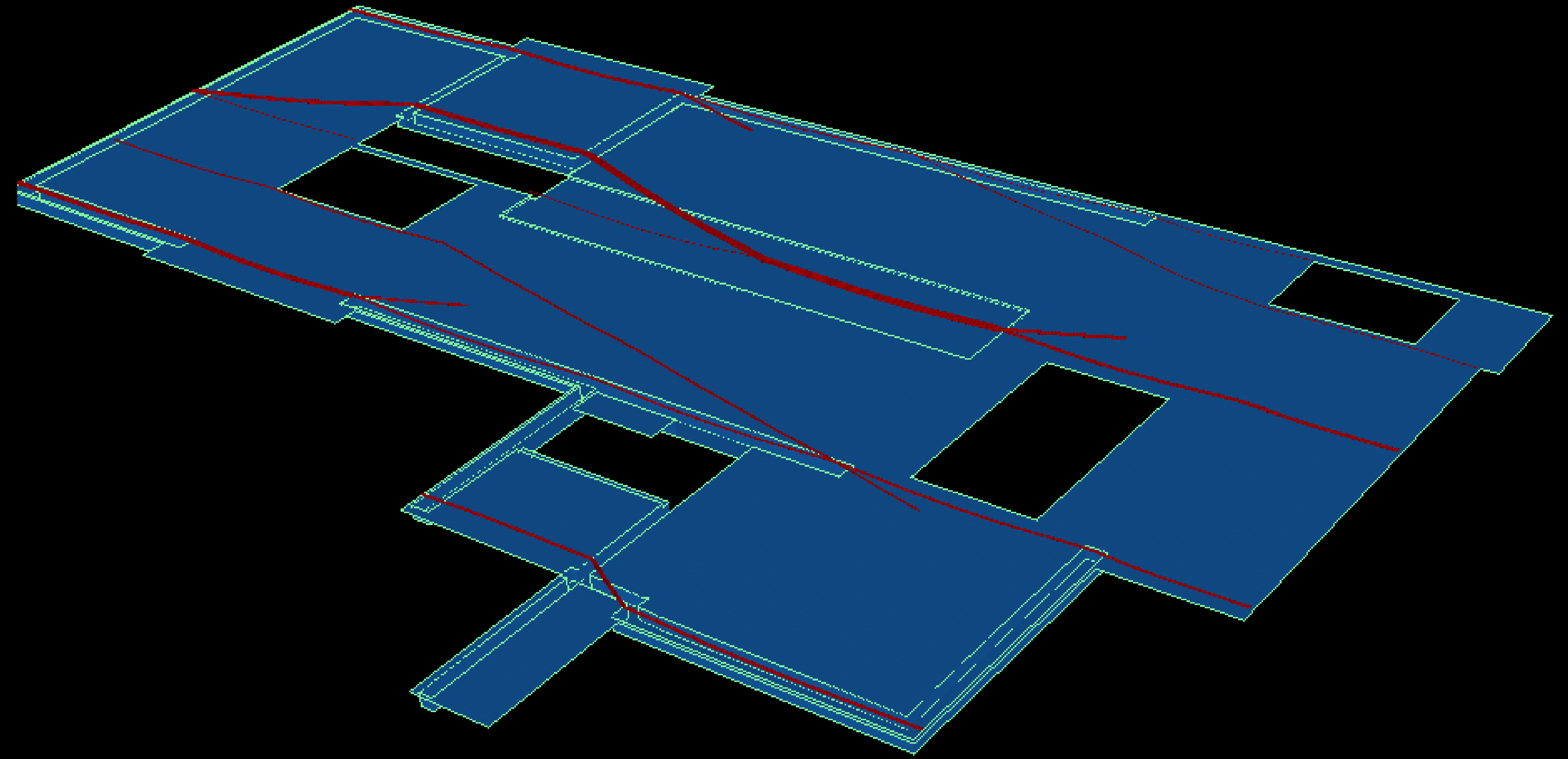
Post-Tensioned Concrete System



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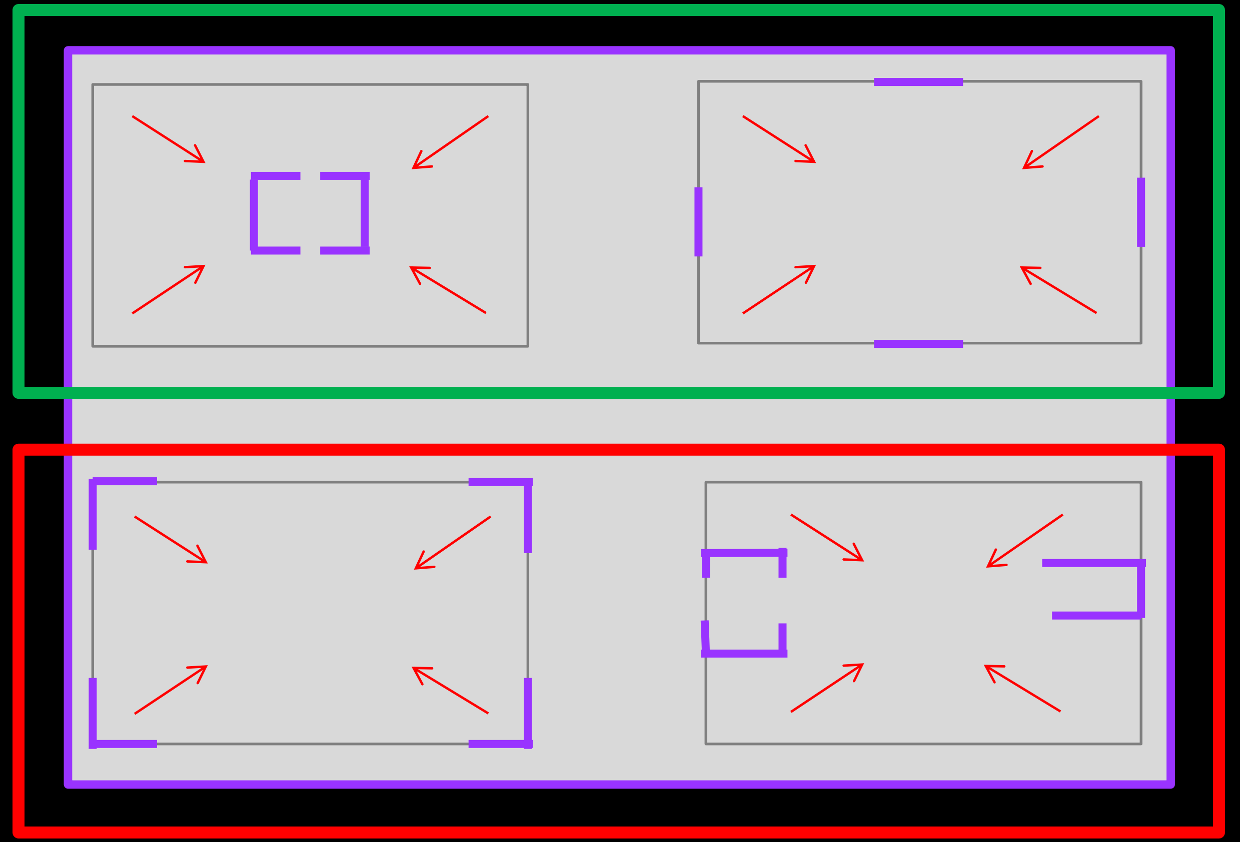
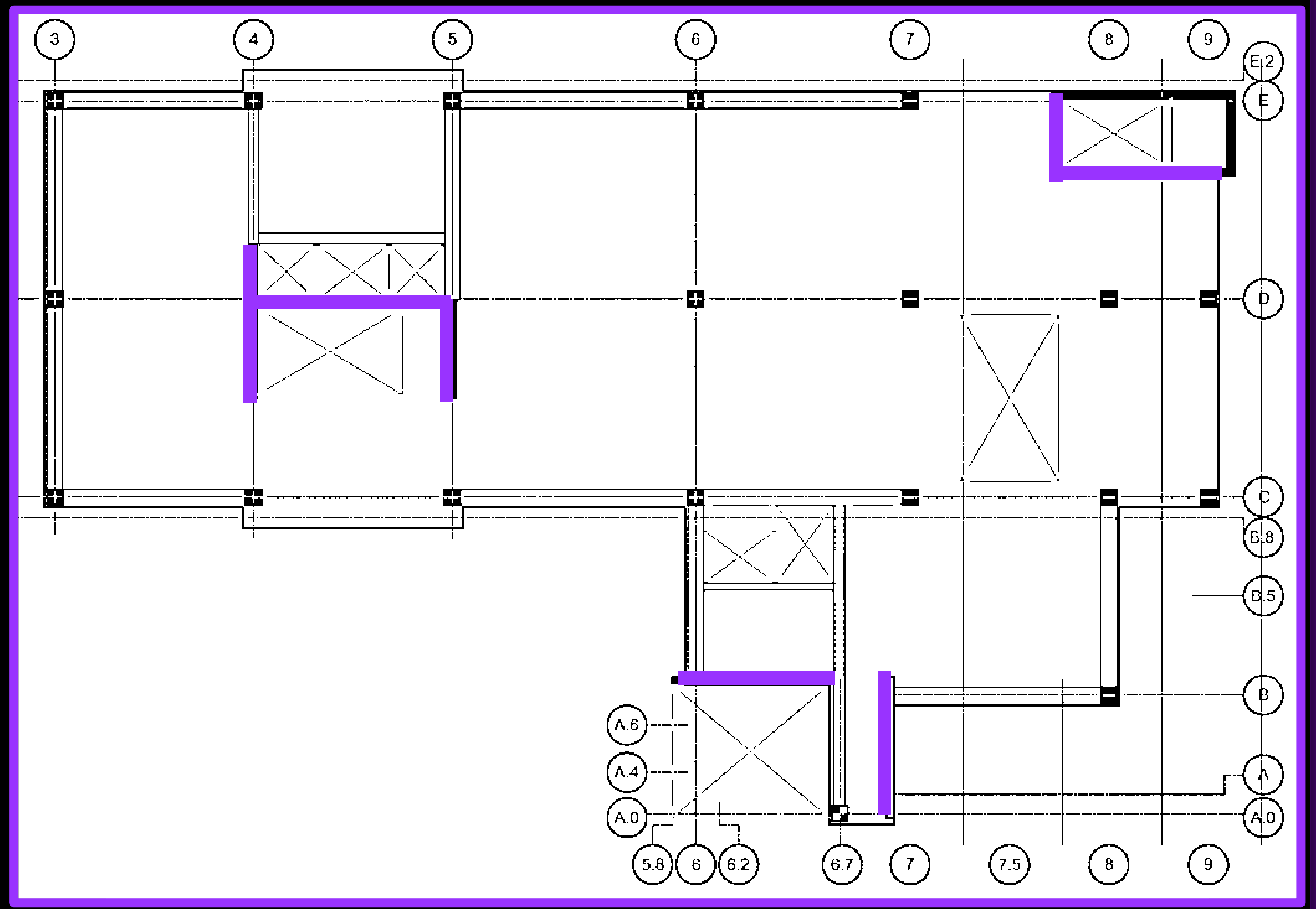
Unfavorable Factors

- Unfavorable Arrangement of Shear Walls and Location of Foundation Walls





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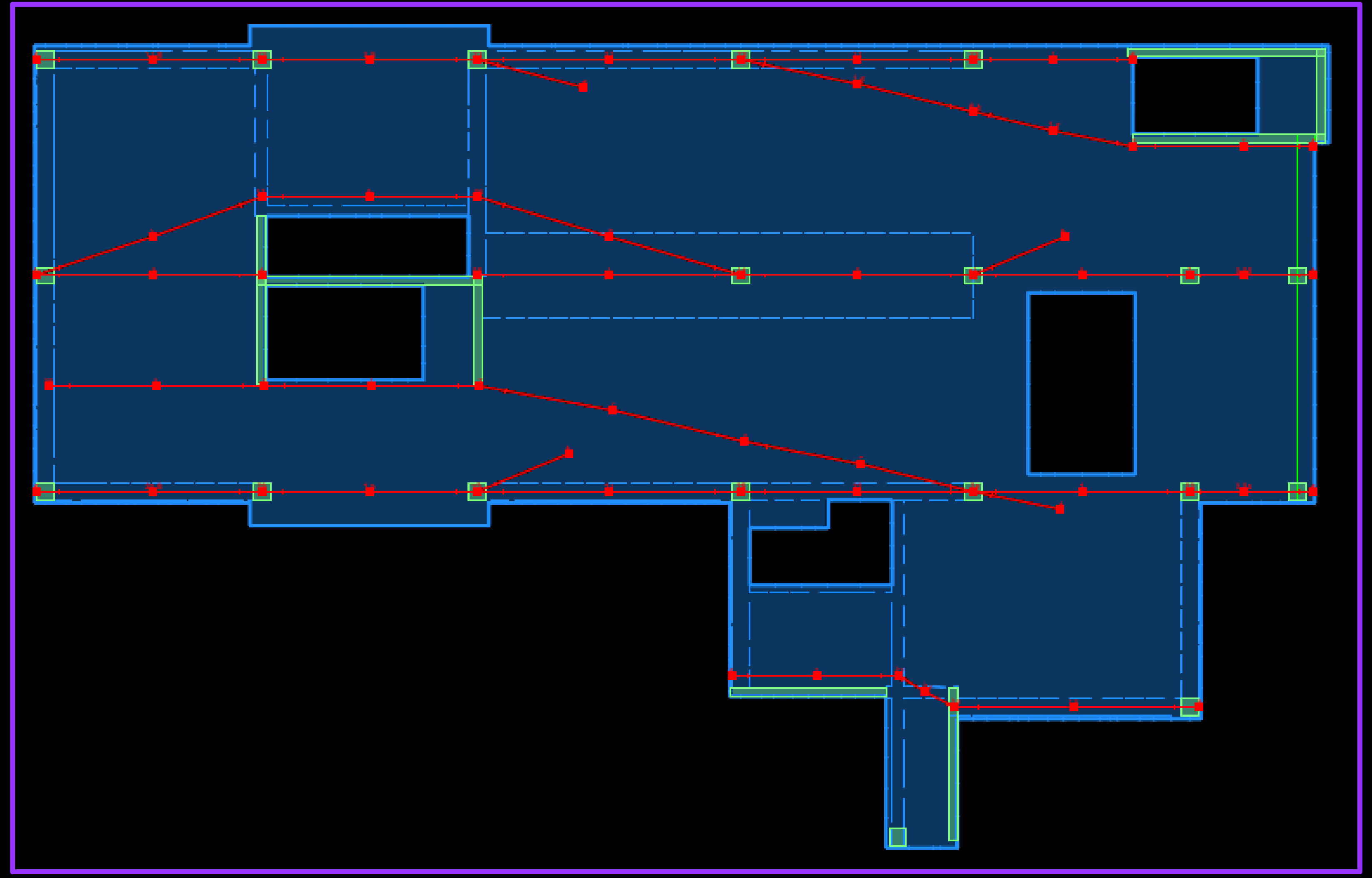
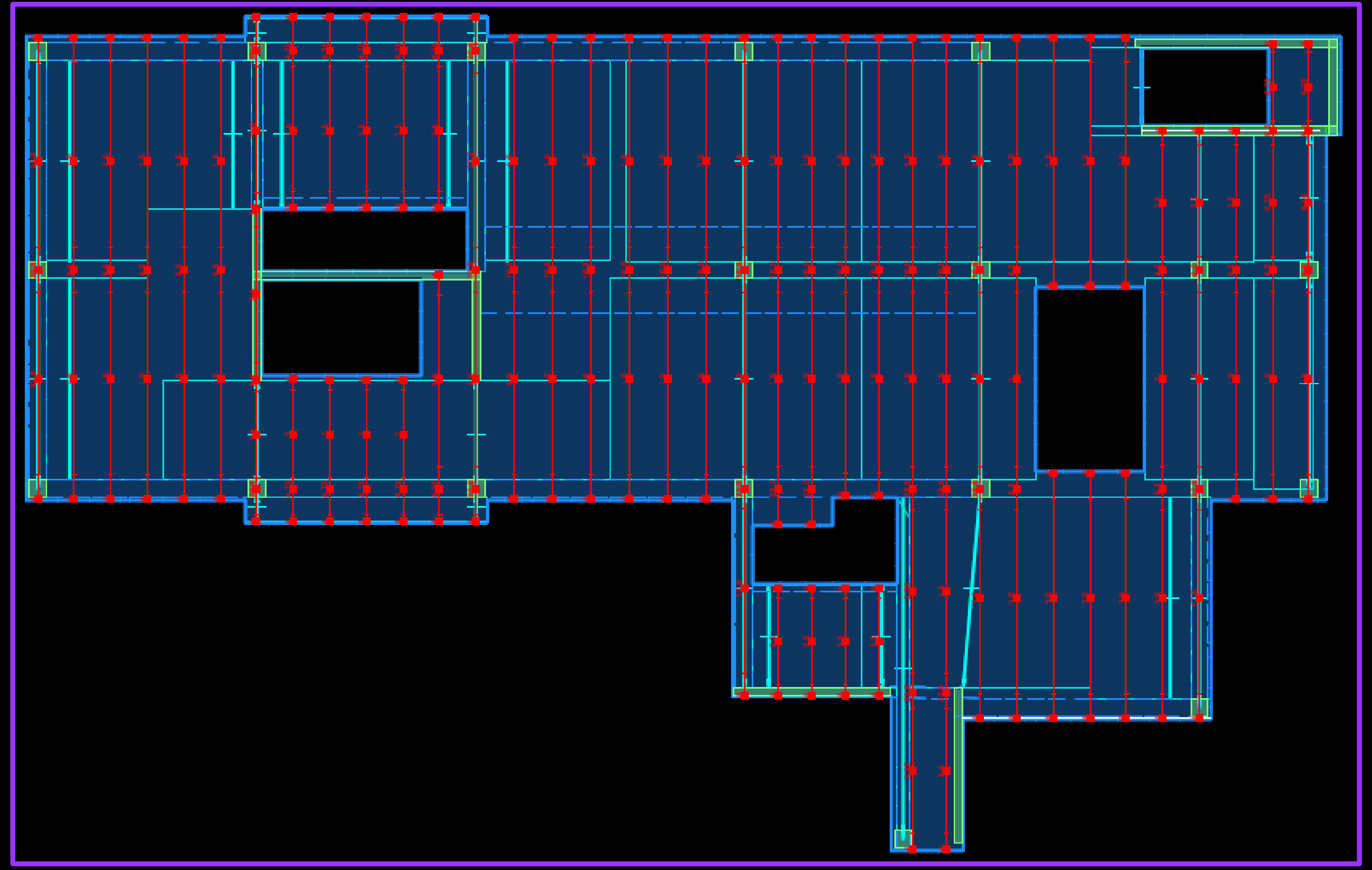
Tendon Layout





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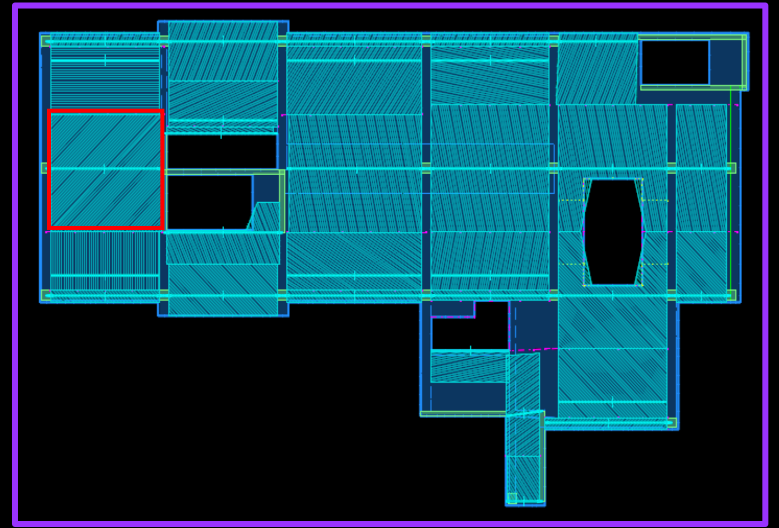
Initial Number of Tendons

- Based on minimum precompression stress = 125 psi
- 27 kips/tendon after all stress losses

Banded Direction:



$A = (24.33')(12/1')(8") = 2429\ in^2$

$P = (125psi)(2429in^2) = 304kips$

$Tendons = \frac{304\ kips}{27\ kips/tendon} = 11\ Tendons$

Distributed Direction:

$(125psi)(12/1')(8") = 12000\ lb/ft$

$x = \frac{5400\ lbs}{12000\ lb/ft} = 4.5\ ft$

ACI318-11 18.12.4 :

Maximum tendon spacing of: Max. | 5 feet / 8 x Slab Thickness

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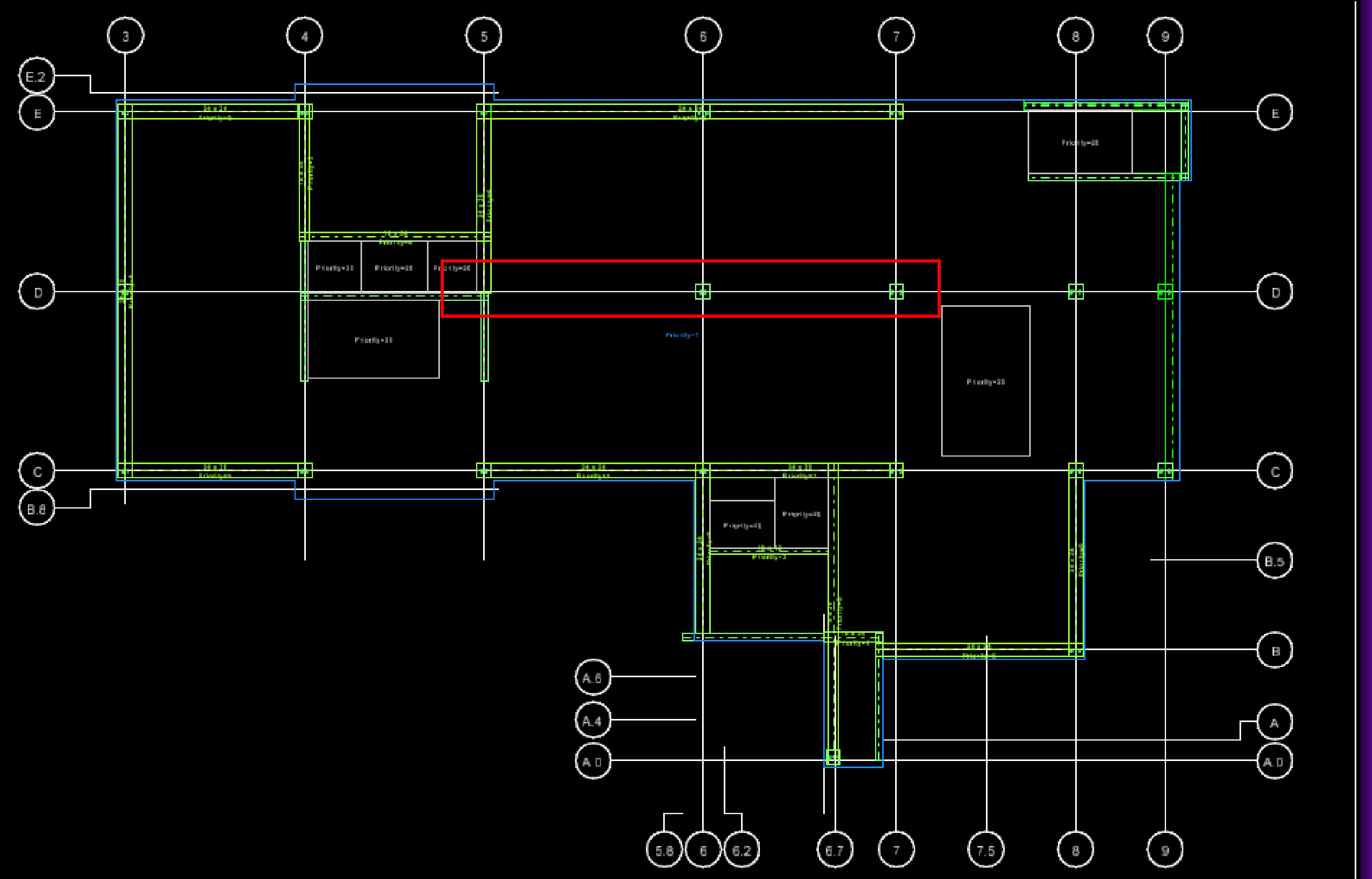
Adjusting Number of Tendons

- Maximum tensile stress = $6\sqrt{f'c}$ = 424.3 psi
- Max precompression stress = 350 psi
- Span D5-D6 and D6-D7:
  - Maximum number of tendons = 32
  - Required number of tendons = 34

FAIL



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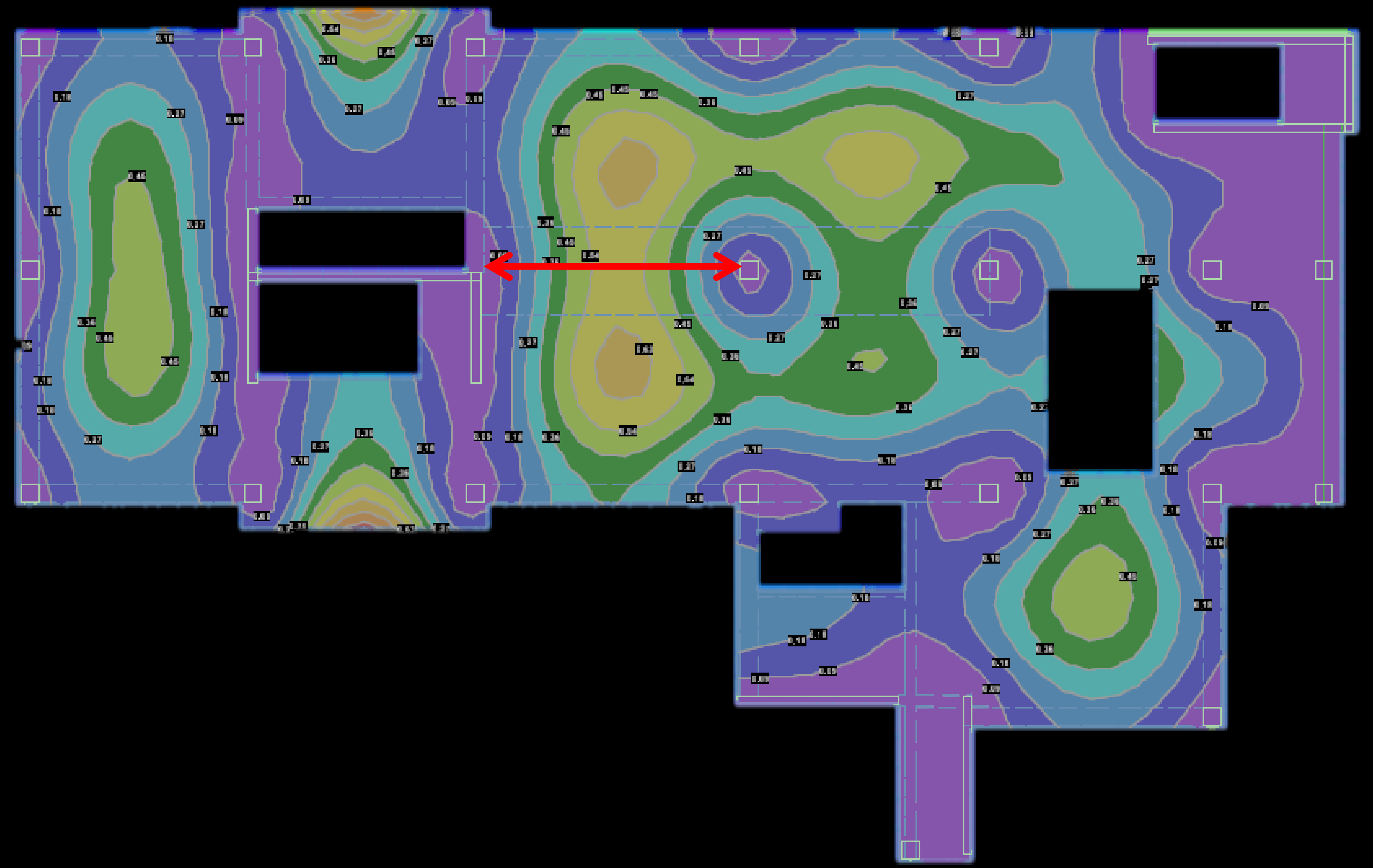
Deflections

- Maximum Allowable Deflection: L/480

- Class U system →
  Deflections calculated using uncracked section properties.

2(Self Dead)+2(Balance)+3(Other-Dead)+1.6(Live)



Span	Length (FT)	Deflection	L/480	Pass/Fail
5D - 6D	31	0.578	0.620	Pass

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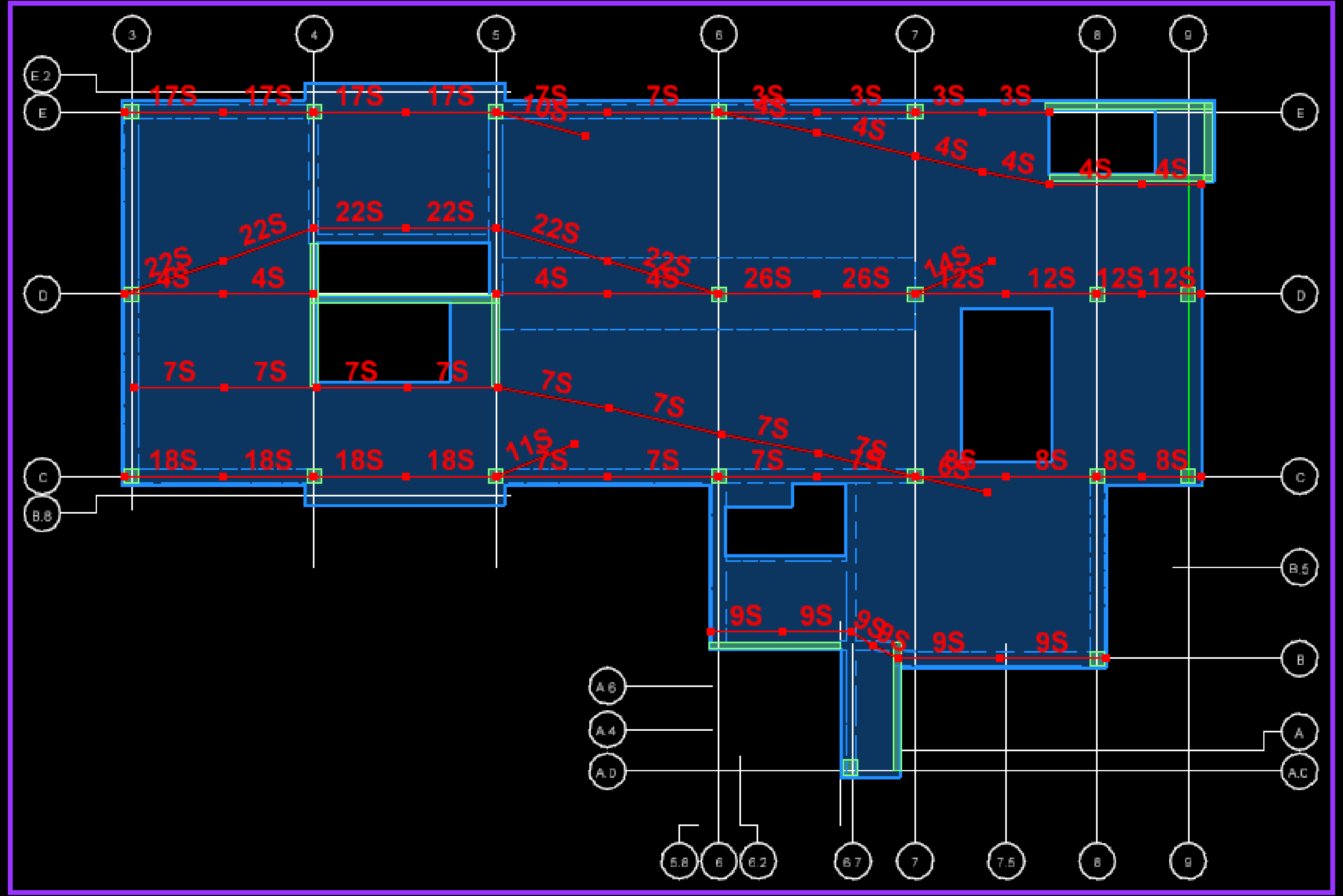
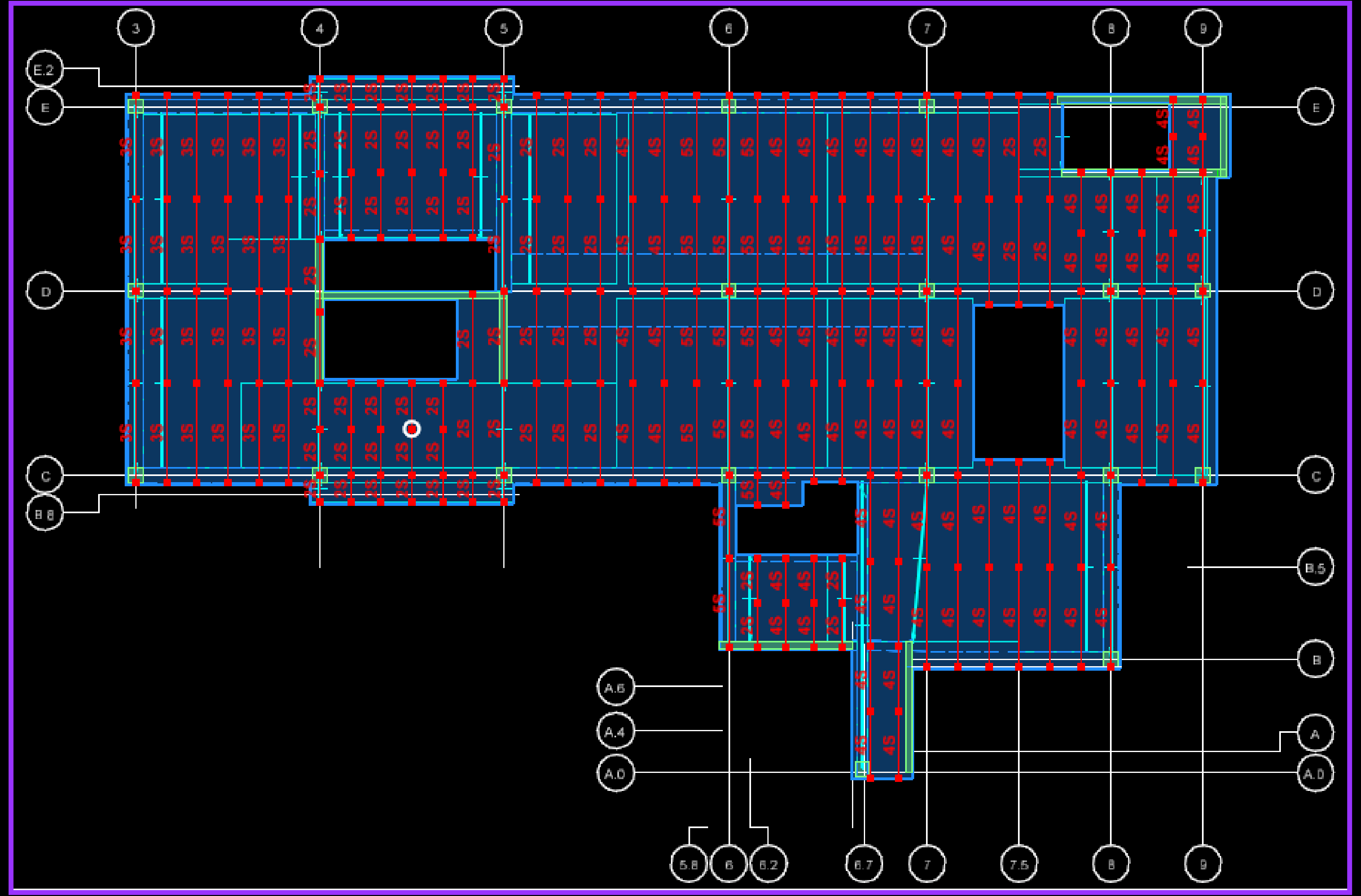
Final Layout





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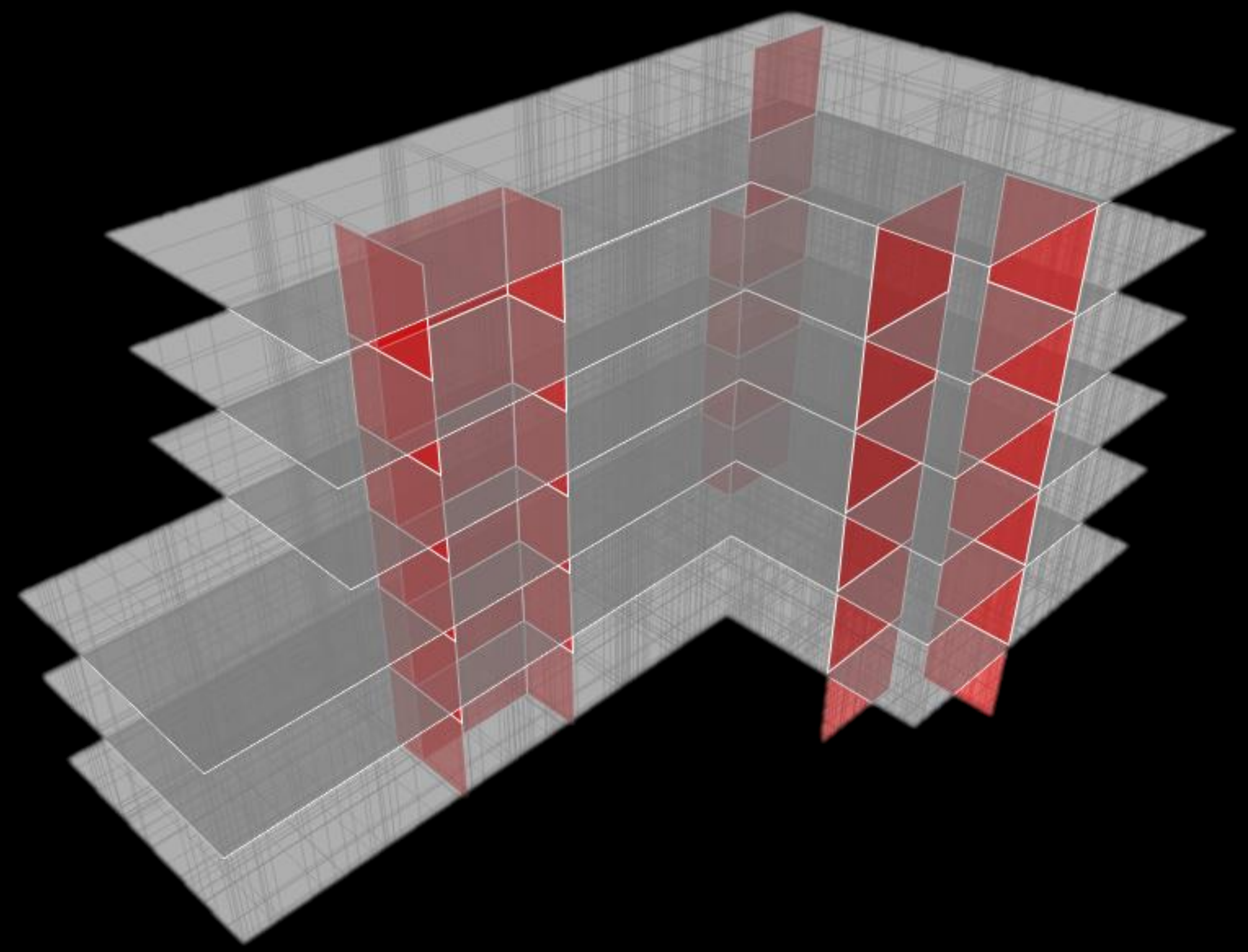
Lateral System Analysis



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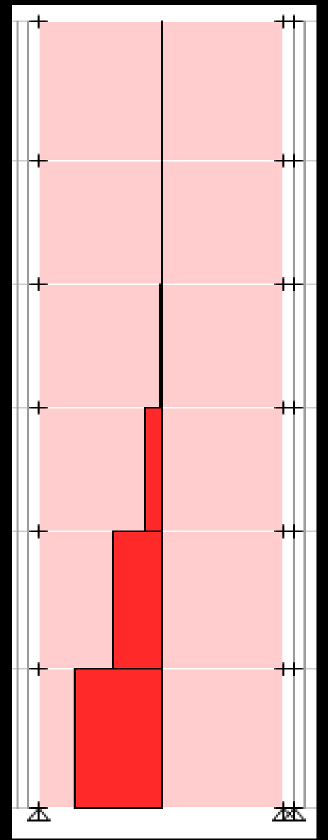
Shear Force Comparison



Max Shear due to Soil Loads: 2294 K

Comparison of Shear Forces		
	Shear Capacity (k)	Force (k)
Original Loads	4752	3071
New Loads	4934	3908
Percent Increase	3.8%	27.3%

Drift Comparison

Max Allowable Building Deflection: 3.1"

Max Allowable Story Drift: 3.2"

Comparison of Maximum Drifts		
	Max Building Deflections (in) [Wind Case 4 +M Same Direction]	Max Story Drift [Y-Direction +M]
Original Loads	2.16	2.81
New Loads	2.72	3.18
Percent Increase	25.9%	13.2%

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Cost and Schedule Analysis

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Steel System Cost

Item	Amount
Fiber Reinforcement	28,317
Normal Weight Fill	144125
Finish Elevated Slab	67,830
Cure and Protect Slab	10,755
Wide Flange Steel Column	208,893
Structural Floor Framing	742,673
Metal Floor Deck	178,797
Spray Fire Proofing	102,629
Total Cost	**$ 1,484,019**

- Structure ~ 3% of total project cost

Concrete System Cost

Item	Amount
Formwork	553622
Structural Concrete	273961
Finishing	42863
Placement	51167
Reinforcement	231115
Total Cost	**$ 1,268,000**

- Reuse of formwork
- +$8 for accelerated slab concrete mix
- +$2/Month for rented column forms

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Cost Comparison

15% Project Cost Savings

Total System Cost	
Steel	Concrete
$ 1,484,019	**$1,268,000**

Per Square Foot Cost	
Steel	Concrete
$ 24.50	**$ 21.00**

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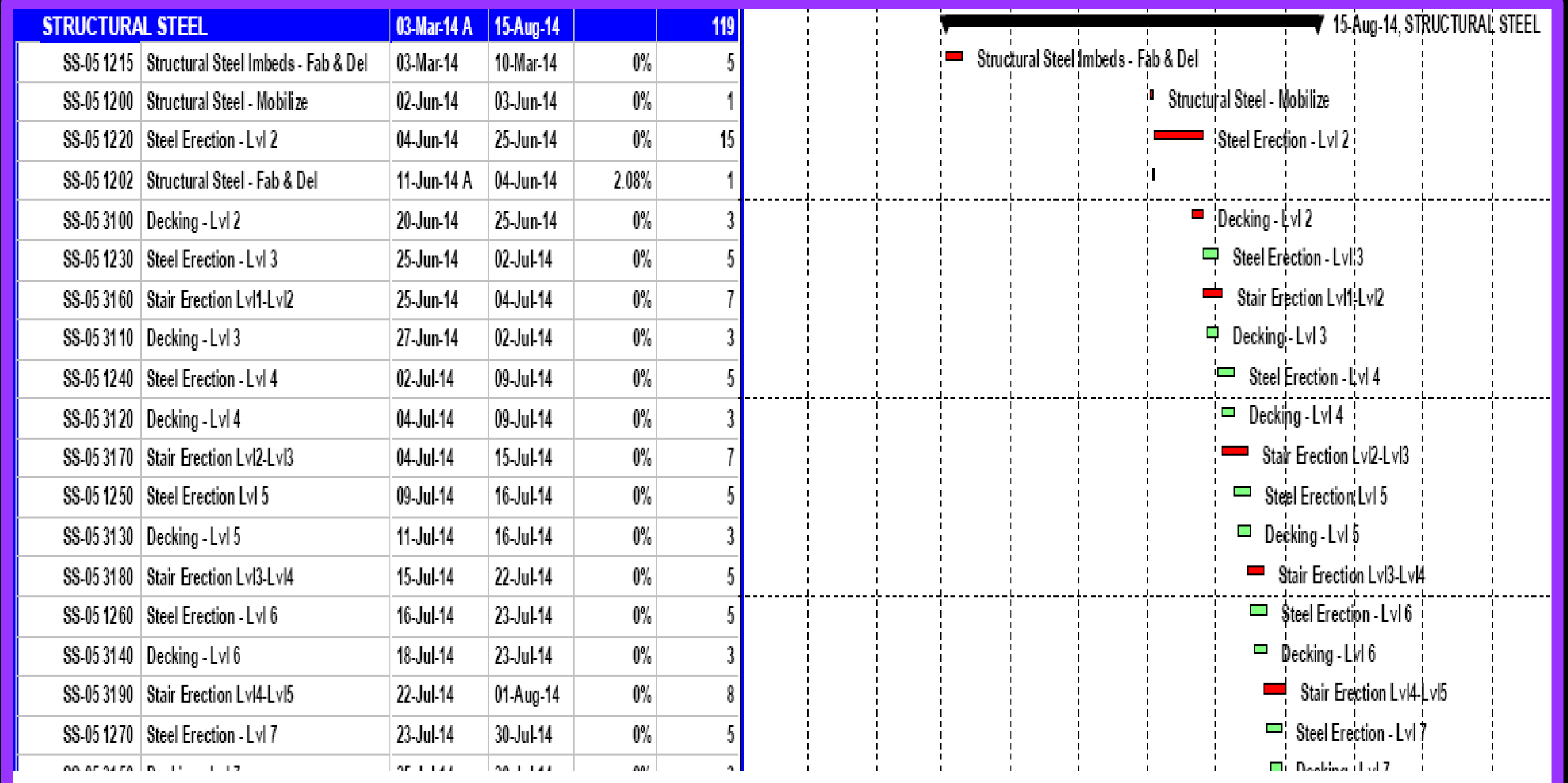
Steel System Schedule

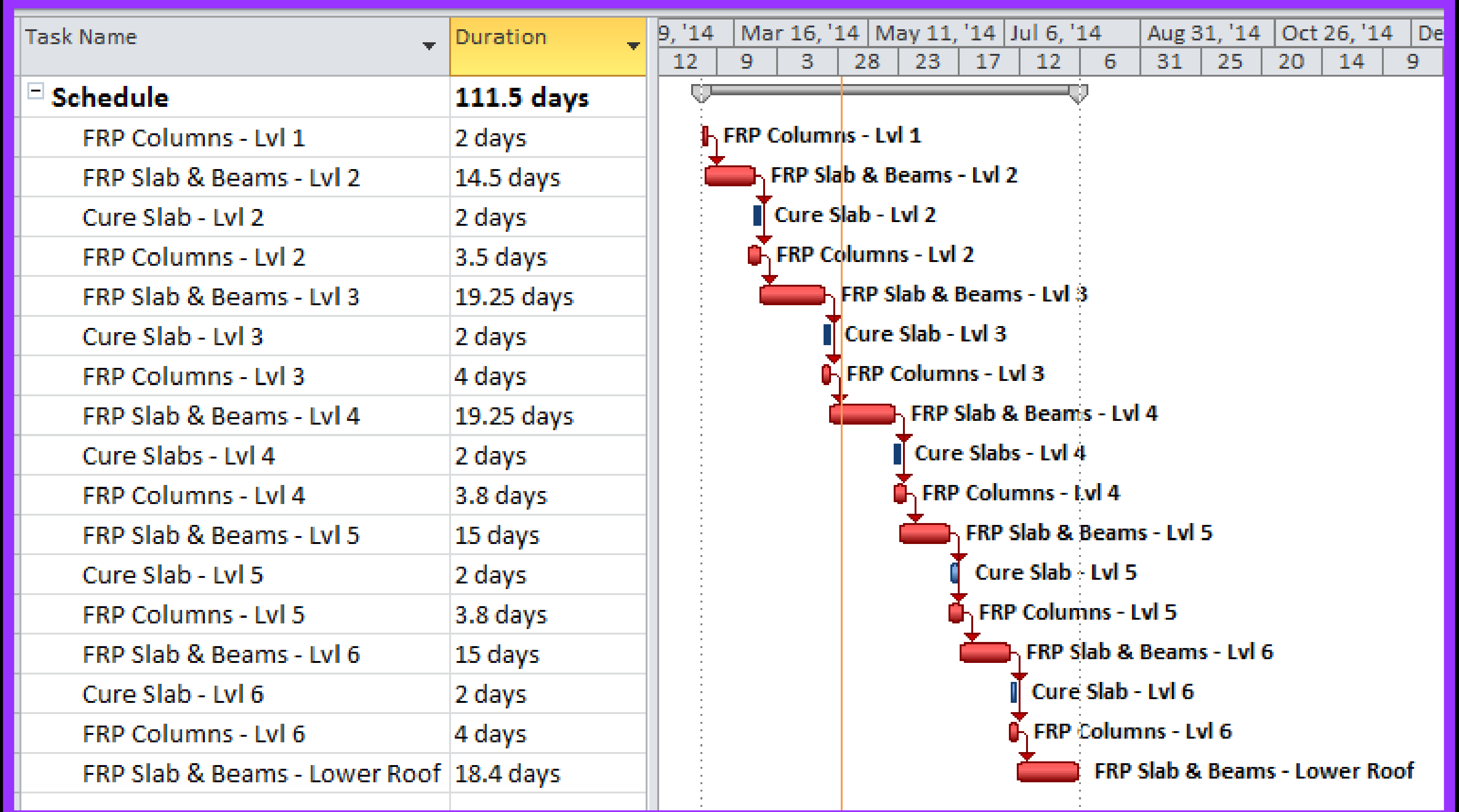


STRUCTURAL STEEL		03-Mar-14 A	15-Aug-14		119
SS-05 1215	Structural Steel Imbeds - Fab & Del	03-Mar-14	10-Mar-14	0%	5
SS-05 1200	Structural Steel - Mobilize	02-Jun-14	03-Jun-14	0%	1
SS-05 1220	Steel Erection - Lvl 2	04-Jun-14	25-Jun-14	0%	15
SS-05 1202	Structural Steel - Fab & Del	11-Jun-14 A	04-Jun-14	2.08%	1
SS-05 3100	Decking - Lvl 2	20-Jun-14	25-Jun-14	0%	3
SS-05 1230	Steel Erection - Lvl 3	25-Jun-14	02-Jul-14	0%	5
SS-05 3160	Stair Erection Lvl1-Lvl2	25-Jun-14	04-Jul-14	0%	7
SS-05 3110	Decking - Lvl 3	27-Jun-14	02-Jul-14	0%	3
SS-05 1240	Steel Erection - Lvl 4	02-Jul-14	09-Jul-14	0%	5
SS-05 3120	Decking - Lvl 4	04-Jul-14	09-Jul-14	0%	3
SS-05 3170	Stair Erection Lvl2-Lvl3	04-Jul-14	15-Jul-14	0%	7
SS-05 1250	Steel Erection Lvl 5	09-Jul-14	16-Jul-14	0%	5
SS-05 3130	Decking - Lvl 5	11-Jul-14	16-Jul-14	0%	3
SS-05 3180	Stair Erection Lvl3-Lvl4	15-Jul-14	22-Jul-14	0%	5
SS-05 1260	Steel Erection - Lvl 6	16-Jul-14	23-Jul-14	0%	5
SS-05 3140	Decking - Lvl 6	18-Jul-14	23-Jul-14	0%	3
SS-05 3190	Stair Erection Lvl4-Lvl5	22-Jul-14	01-Aug-14	0%	8
SS-05 1270	Steel Erection - Lvl 7	23-Jul-14	30-Jul-14	0%	5

Image Courtesy of Cannon Design

- Construction length: 119 days
- March 3rd, 2014 – August 15th, 2014

Concrete System Schedule



Task Name	Duration
Schedule	111.5 days
FRP Columns - Lvl 1	2 days
FRP Slab & Beams - Lvl 2	14.5 days
Cure Slab - Lvl 2	2 days
FRP Columns - Lvl 2	3.5 days
FRP Slab & Beams - Lvl 3	19.25 days
Cure Slab - Lvl 3	2 days
FRP Columns - Lvl 3	4 days
FRP Slab & Beams - Lvl 4	19.25 days
Cure Slabs - Lvl 4	2 days
FRP Columns - Lvl 4	3.8 days
FRP Slab & Beams - Lvl 5	15 days
Cure Slab - Lvl 5	2 days
FRP Columns - Lvl 5	3.8 days
FRP Slab & Beams - Lvl 6	15 days
Cure Slab - Lvl 6	2 days
FRP Columns - Lvl 6	4 days
FRP Slab & Beams - Lower Roof	18.4 days

- Construction length: 112 days
- March 3rd, 2014 – April 5th, 2014

UVA's New Library

- Building Introduction
- Problem Statement & Solution
- Two-way System
- PT System
- Lateral System
- **Cost and Schedule Analysis**
  - Cost Analysis
  - Schedule Analysis
- System Comparison
- Conclusion

Schedule Comparison

7 Day Project Duration Decrease

Total System Duration	
Steel	Concrete
119 Days	**112 Days**

UVA's New Library

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- **System Comparison**
- Conclusion

System Comparison

- Construction Type
  - Steel: 1B
  - Concrete: 1B

→ No Change

- Floor Depth

Member	Steel	Concrete
Slab/Floor (in)	6.5	10
Interior Beam (in)	16	-
Interior Girder (in)	24	24
Maximum Edge Beam (in)	30	30
Total Decrease	**6.5 in – 12.5 in**	

- Cost
  - Steel: $1.5 Million
  - Concrete: $1.2 Million

→ 15% Savings

- Construction Time
  - Steel: 119 Days
  - Concrete: 112 Days

→ 7 Day Decrease

- Special Consideration:
  - Concrete Construction Crew

UVA's New Library

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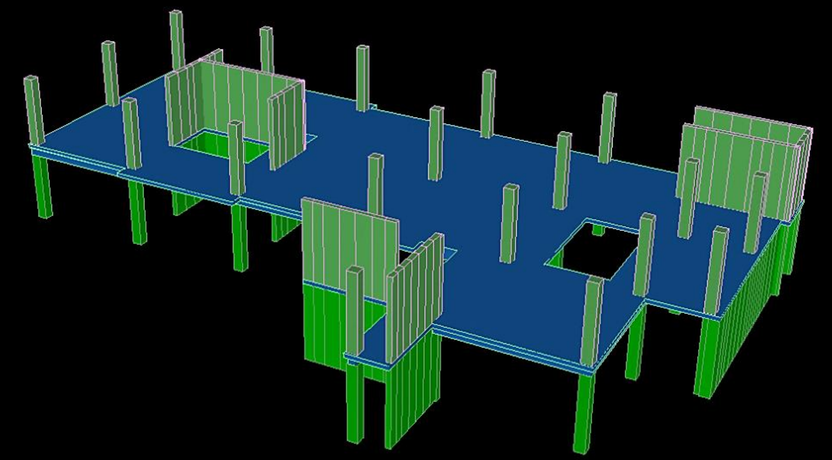
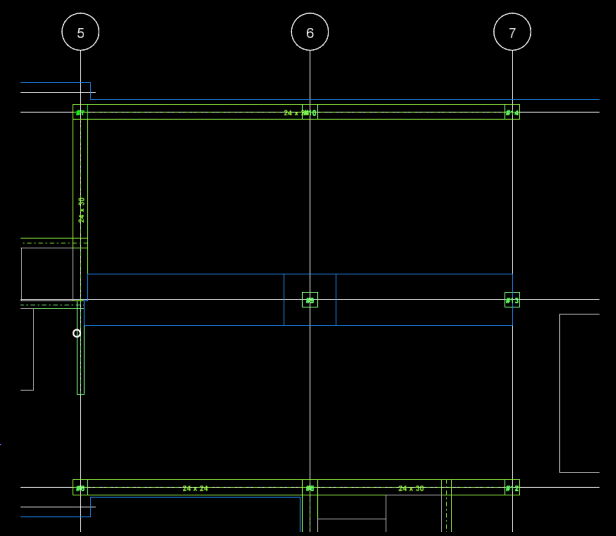
- **Conclusion**

Conclusions

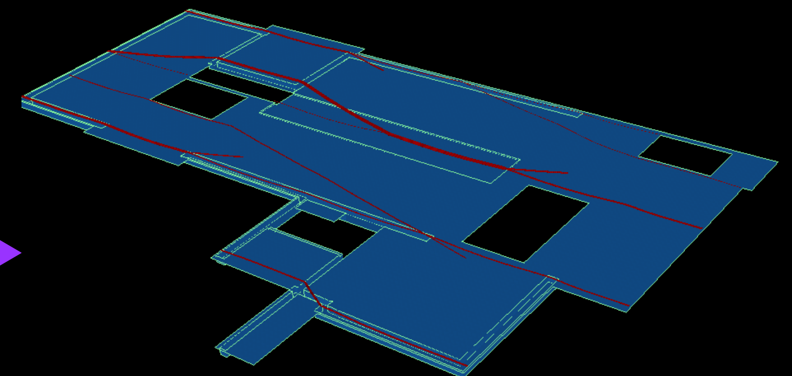
Proposed Goals

- Redesign structural systems as a two-way concrete slab system





- Address deflections in longer span bays
- Investigate the feasibility of a post-tensioned system



- Determine feasibility of a concrete system
  - Consider cost and schedule impact

27% Cost Savings + 7 Day Schedule Decrease

UVA's New Library

- Building Introduction
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- Cost and Schedule Analysis
- System Comparison
- **Conclusion**

Acknowledgements

- *A Special Thanks to:*
  - Cannon Design | Rachel Chicchi
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  - AE Faculty | Professor Heather Sustersic
  - My Family, Fiancé, and Friends
  - Jesus Christ

Image Courtesy of Cannon Design

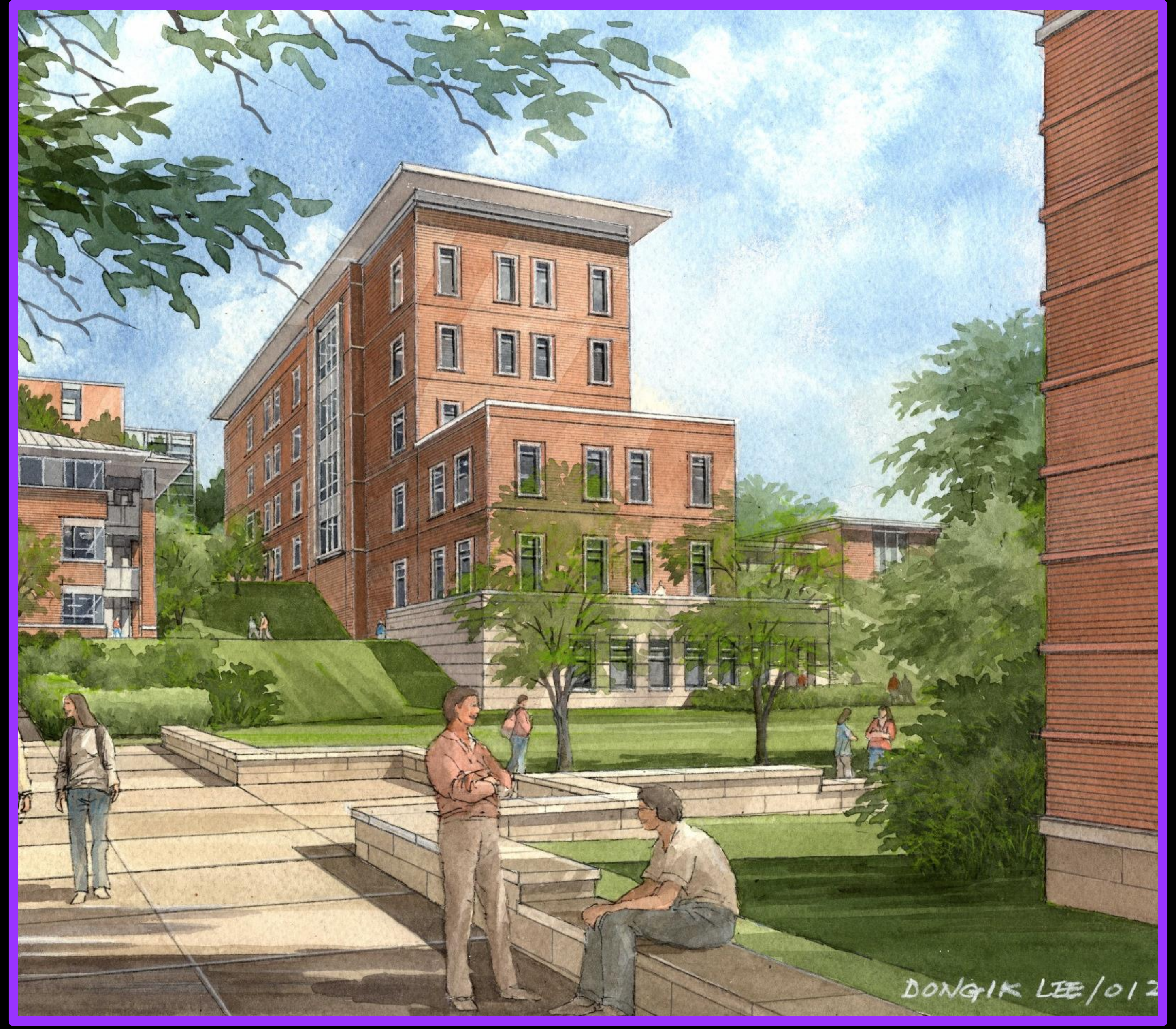

Image Courtesy of Cannon Design

Questions and Comments?


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Appendix Slides

Verification of Output	PT Deflections	Waterproof Membranes
Balancing Tendons	Edge Deflections	Drainage Calculations
Two-way Deflections	Water Path	

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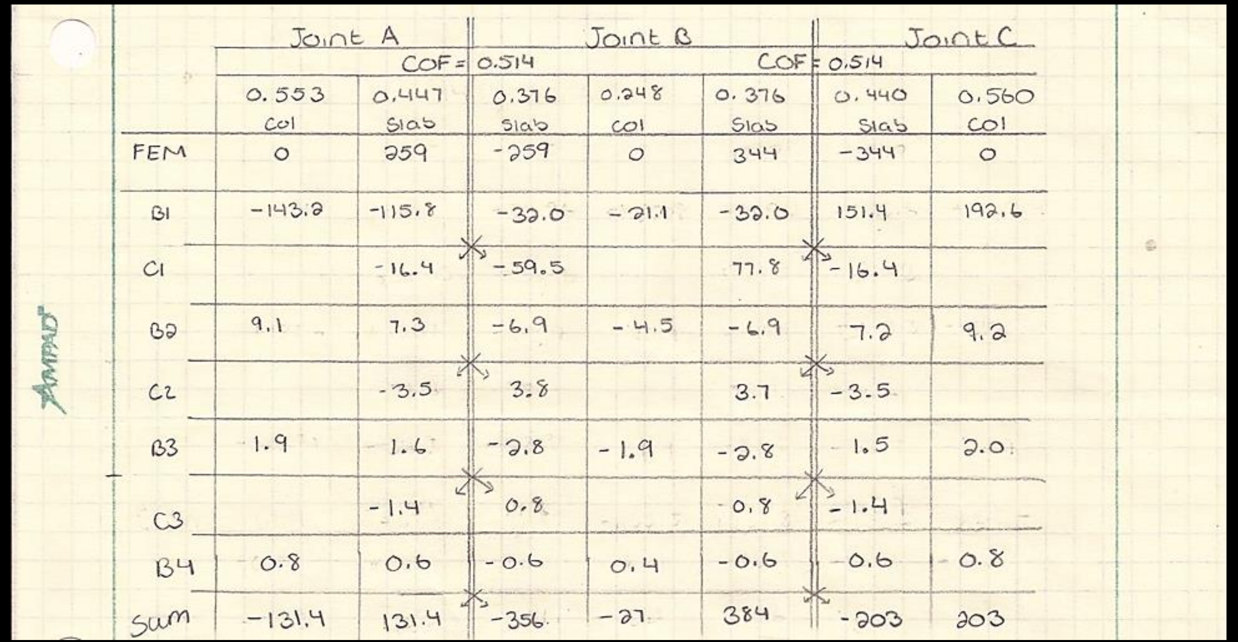
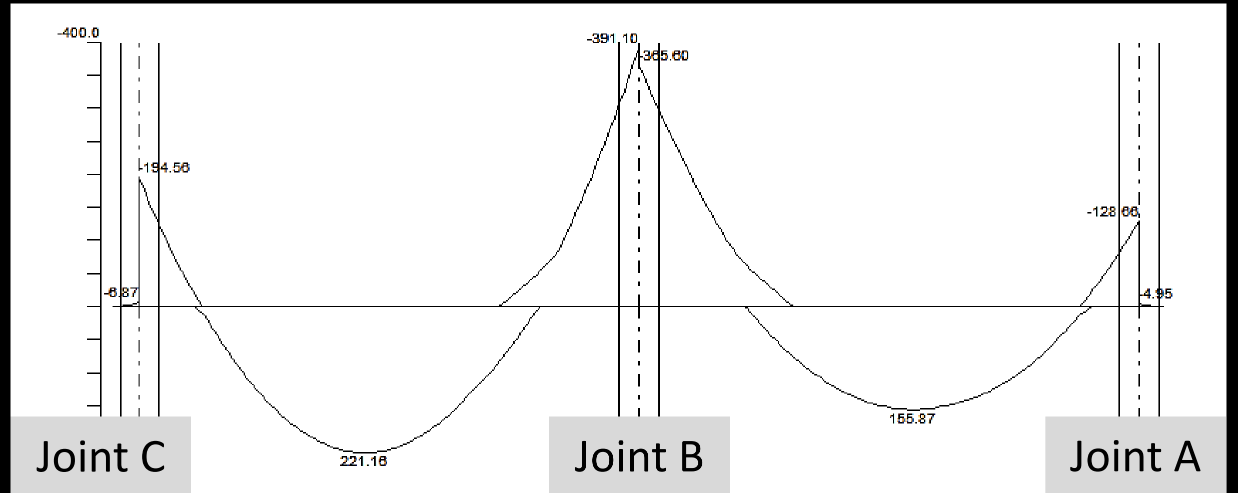
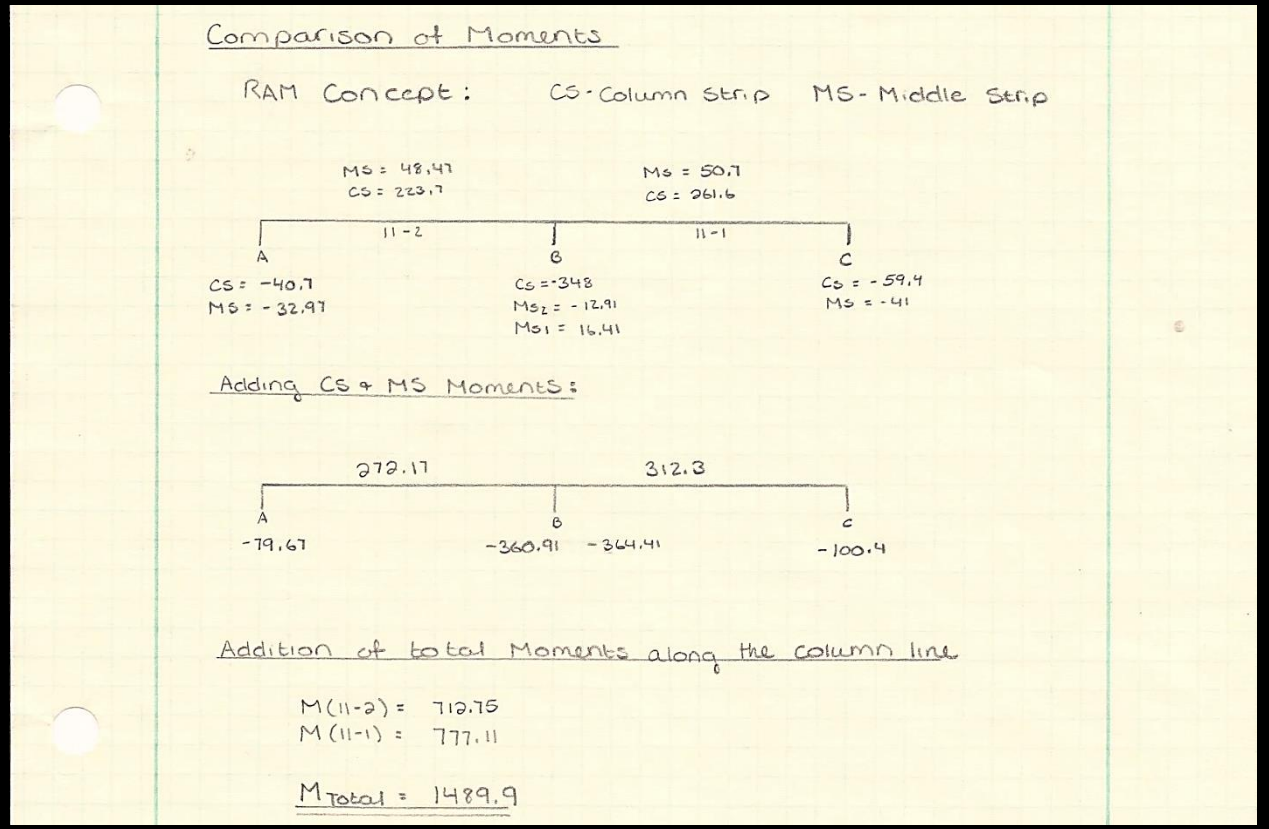
Verification of Output



	Joint A		Joint B			Joint C	
		COF = 0.514			COF = 0.514		
	0.553 Col	0.447 Slab	0.376 Slab	0.248 Col	0.376 Slab	0.440 Slab	0.560 Col
FEM	0	259	-259	0	344	-344	0
B1	-143.2	-115.8	-32.0	-21.1	-32.0	151.4	192.6
C1		-16.4	-59.5		77.8	-16.4	
B2	9.1	7.3	-6.9	-4.5	-6.9	7.2	9.2
C2		-3.5	3.8		3.7	-3.5	
B3	1.9	1.6	-2.8	-1.9	-2.8	1.5	2.0
C3		-1.4	0.8		0.8	-1.4	
B4	0.8	0.6	-0.6	0.4	-0.6	0.6	0.8
Sum	-131.4	131.4	-356	-27	384	-203	203





Comparison of Moments

RAM Concept: CS - Column Strip MS - Middle Strip

MS = 48.47
CS = 223.7
MS = 50.7
CS = 261.6
11-2
11-1
A
CS = -40.7
MS = -32.97
B
CS = -348
MS_2 = -12.91
MS_1 = 16.41
C
CS = -59.4
MS = -41

Adding CS & MS Moments:

272.17
312.3
A
-79.67
B
-360.91 -364.41
C
-100.4

Addition of total Moments along the column line

M(11-2) = 712.75
M(11-1) = 777.11

M_{Total} = 1489.9

Percent Different in Total Design Moments			
	Hand Calculations/SP Slab	RAM Concept	% Difference
Total Moment in Span A-B	650.13	712.75	9%
Total Moment in Span B-C	806.82	777.11	4%
Total Moment in Both Spans	1456.95	1489.86	2%

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Verification of Output

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One-Way Shear			
	RAM Concept	Hand Calculations	% Difference
Max Shear Demand	143.1 K	143.1 K	0%
Max Capacity	302.6K	278.4 K	8%

Two-Way Shear			
	RAM Concept	Hand Calculations	% Difference
Max Shear Demand	284.6 K	280 K	1.6%
Max Capacity	189.7 K	189.9 K	0.1%

Shear Stud Rail Design		
	RAM Concept	Decon STDesign
Stud Rails per Column	12	12
Studs per Stud Rail	12	13
Stud Spacing	3.75 in	3.75

Balancing the Tendons

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- Balancing Load = weight of design strip
- Lower Limit = 50% of design strip weight
- Upper Limit = 125% of design strip weight

Two-way System Deflections

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- ECR in RAM Concept:
  - Default ECR = 3.35 (ACI209)
  - To account for cracking RAM Concept uses a conservative approach:
    - New ECR = ECR * ($M_{service}$/M_{crack})

- Initial ECR Adjustment:
  - ACI318-11
    - Initial factor = 1
    - Long term factor = 2 (5 + Years w/ no compression reinforcement)
  - Adjusted ECR = 3

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Two-way System Deflections

- Trial 1: Weighted Average

$$\frac{\text{Live Load}}{\text{Live Load+Dead Load}}(1.6) + \frac{\text{Dead Load}}{\text{Live Load+Dead Load}}(\text{ECR})$$

$$\frac{80}{80+141.5}(1.6) + \frac{141.5}{80+141.5}(3) = 2.5$$

Span	Length (FT)	Deflection	L/?	Pass/Fail
5D - 6D	31	1.27	0.775	Fail

- Trial 2: Compression Reinforcement
  - Compression reinforcement changes the long term deflection factor
  - Based on trial runs in RAM Concept an ECR < 1 from compression reinforcement would be required → Unrealistic!

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Two-way System Deflections

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- Trial 3: Drop Panel
  - First size: 6' x 6' x 6"

Span	Length (FT)	Deflection	L/480	Pass/Fail
5D - 6D	31	1.0	0.775	Fail
6D - 7D	27.33	0.669	0.683	Pass
5E - 6D	40	1.07	1.0	Fail
6E - 7D	37.33	0.971	0.933	Fail
5C - 6D	40	1.04	1.0	Fail

- Second size: 7' x 7' x 6"

Span	Length (FT)	Deflection	L/480	Pass/Fail
5D - 6D	31	0.955	0.775	Fail
6D - 7D	27.33	0.592	0.683	Pass
5E - 6D	40	1.03	1.0	Fail
6E - 7D	37.33	0.92	0.933	Pass
5C - 6D	40	0.986	1.0	Pass

Two-way System Deflections

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- Trial 4: Larger Drop Panel or Shallow Beam
  - Drop Panel: 8' x 8' x 6"

Span	Length (FT)	Deflection	L/480	Pass/Fail
5D - 6D	31	0.943	0.775	Fail
6D - 7D	27.33	0.614	0.683	Pass
5E - 6D	40	1.02	1.0	Fail
6E - 7D	37.33	0.943	0.933	Fail
5C - 6D	40	0.974	1.0	Pass

  - Shallow Beam: 7' x 7' x 4"

Span	Length (FT)	Deflection	L/480	Pass/Fail
5D - 6D	31	0.709	0.775	Pass
6D - 7D	27.33	0.511	0.683	Pass
5E - 6D	40	0.875	1.0	Pass
6E - 7D	37.33	0.817	0.933	Pass
5C - 6D	40	0.827	1.0	Pass

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PT System Deflections

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- ACI318-11 Section 9.5.2.5:
  - Long term deflection factor of 5 or more years= 2
- Sustained loads = DL + SW + portion of LL
- 30% sustained LL for commercial building occupancies of office and residential
- SW DL not counted in instantaneous deflections due to these deflections happening prior to the attachment of non-structural elements

- Total Deflection

  =Service instantaneous + Long term

  =(SID +LL) +2(SW DL + SID+0.3LL)

  =2(SW DL) + 3(SID) + 1.6(LL)

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Edge Deflections: Two-way

Span	Span Length (FT)	Initial Deflections (in)	Final Deflections (in)	Sustained Deflections (in)	L/600 (in)	Pass/Fail
3C-D3	25.33	0.018	0.19	0.17	0.51	Pass
D3-E3	25.33	0.016	0.18	0.16	0.51	Pass
3E-4E	25.33	0.037	0.31	0.27	0.51	Pass
4E-5E	25.33	0.059	0.55	0.49	0.51	Pass
5E-6E	31	0.044	0.52	0.48	0.62	Pass
6E-7E	27.33	0.020	0.35	0.33	0.55	Pass
7E-8E	25.33	0.007	0.18	0.17	0.51	Pass
9D-9C	23.33	0.000	0.03	0.03	0.47	Pass
9C-8C	12.67	0.000	0.10	0.10	0.25	Pass
8B-7B	25.33	0.060	0.50	0.44	0.51	Pass
6C-5C	31	0.045	0.53	0.49	0.62	Pass
5C-4C	25.33	0.059	0.56	0.50	0.51	Pass
4C-3C	25.33	0.029	0.23	0.20	0.51	Pass

Edge Deflections: PT

Span	Span Length (FT)	Deflections (in)	L/600 (in)	Pass/Fail
3C-D3	25.33	0.14	0.51	Pass
D3-E3	25.33	0.13	0.51	Pass
3E-4E	25.33	0.21	0.51	Pass
4E-5E	25.33	0.47	0.51	Pass
5E-6E	31	0.32	0.62	Pass
6E-7E	27.33	0.21	0.55	Pass
7E-8E	25.33	0.21	0.51	Pass
9D-9C	23.33	0.03	0.47	Pass
9C-8C	12.67	0.03	0.25	Pass
8B-7B	25.33	0.23	0.51	Pass
6C-5C	31	0.37	0.62	Pass
5C-4C	25.33	0.50	0.51	Pass
4C-3C	25.33	0.25	0.51	Pass

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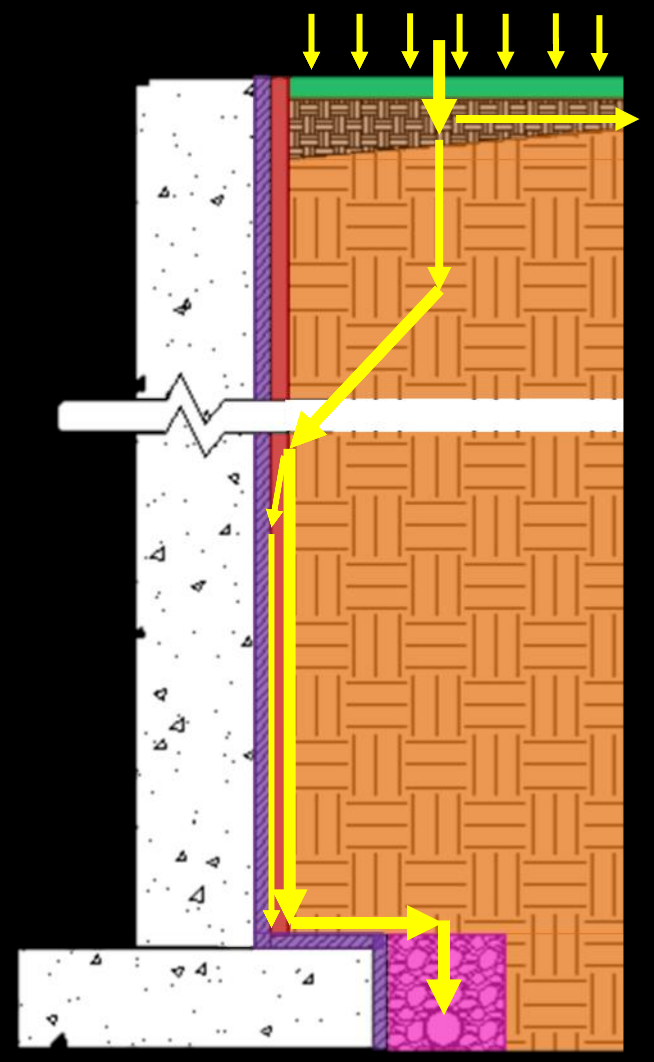
Water Path



1. Top Soil
2. Compacting Clay
3. Backfill
4. Protection Board
5. Waterproofing Membrane
6. VADOT 57 Stone

Compacting Clay
- 10" – 12" Thick
- Thins out to top soil 12'-20' from building

Backfill
-recommended by geotechnical engineer
-full gradation soil with minimal fines

Protection Board
-1/2" thick
-plastic & geotextile material

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Waterproofing Membranes

- Foundation Wall: Bituthane System 4000
  - Thickness: 1/16th
  - Excellent adhesion to the wall through the use of the System 4000 Surface Conditioner
    - Water based, latex surface treatment
    - High tack finish to the treated subtract
    - Formulated to bind site dust and concrete efflorescence
  - Reduces inventory and handling costs by packaging the conditioner and membrane together

- Basement Slab: Bituthane System 4000
  - Thickness: ½"
  - Installed between the mud slab and floor slab
  - Forms a permanent seal against ground water
  - High tensile strength to provide resistance against the stress of ground settlement

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Drainage Calculations

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- At the time of boring all holes were dry
- 48-72 hours later all holes showed water levels
- All holes were 3 ¼" in diameter

Compare Depth of Footing to Water Level Measurements				
Boring Number	Location	Top of Footing	Bottom of Footing	Elevation of Water Level
B-1	Outside of building footprint - West side	-	-	2484.0
B-2	Outside of building footprint - West side	-	-	2463.5
B-3	Outside of building footprint - North-west side	2476.5	2474.83	2471.6
B-4	Inside of building footprint	2476.5	2474.83	2474.4
B-5	Inside of building footprint	2476.5	2474.83	-
B-6	Inside of building footprint	2474	2472.33	2494.3
B-7	Outside of building footprint - East side	2476.5	2474.25	2503.0
B-8	Outside of building footprint - East side	2476.5	2474.25	2511.0

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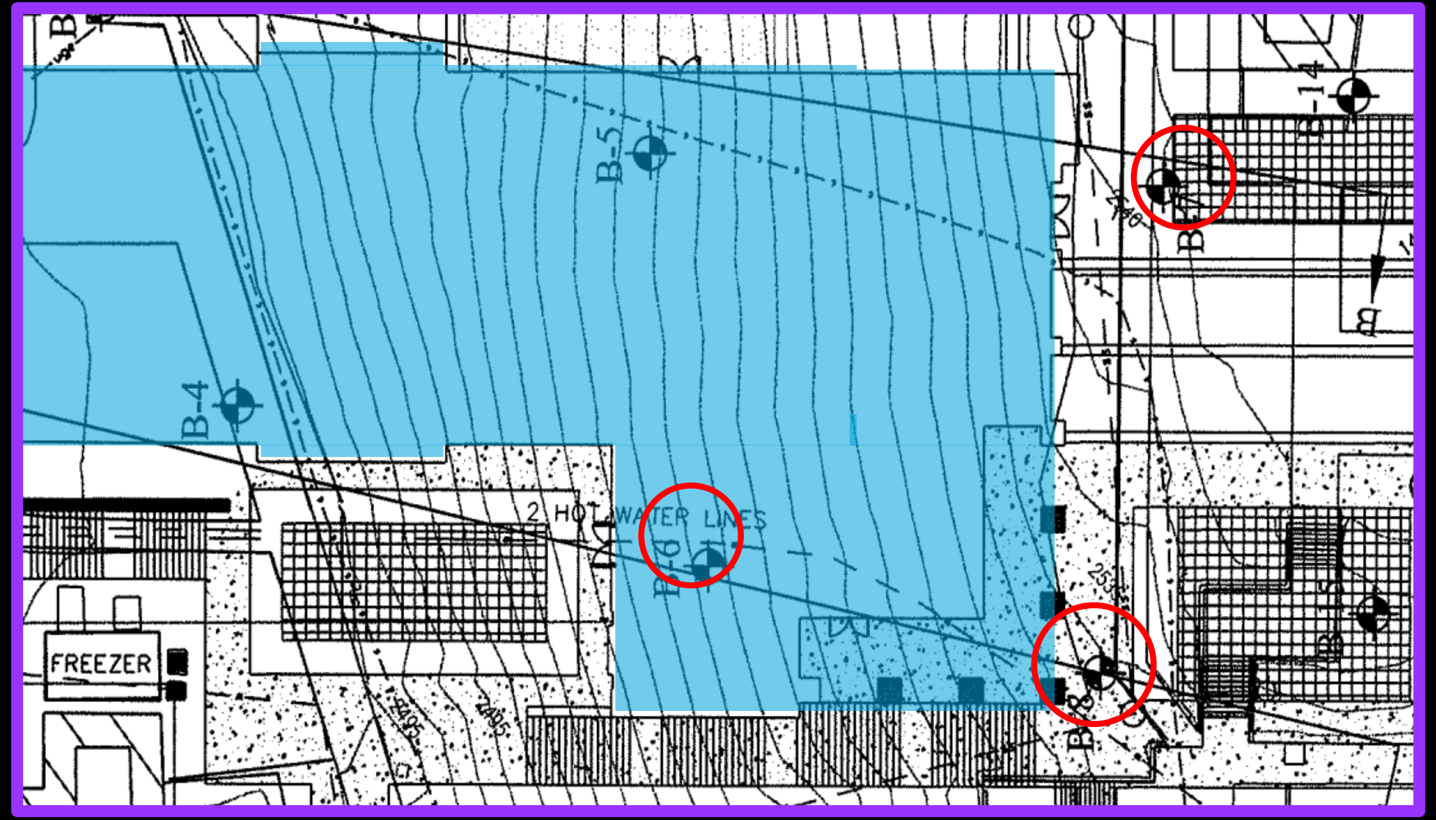
Drainage Calculations



Flow Rate of Ground Water						
Boring Number	Depth (FT)	Area of Bore Hole (FT^2)	Depth * Area (FT^3)	Number of Hours	Flow Rate (FT^3/HR)	Flow Rate (gpm)
B-6	22	8.29	182.4	48	4	0.4738
B-7	46	8.29	381.4	72	5	0.6604
B-8	59	8.29	489.2	72	7	0.8470

Drainage Calculations

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- Average rainfall rates Bristol, VA = 0.028 gpm/SF

- Tributary Area:
  - 10' away from structure (half the distance to the surrounding storm drain)
  - 2870 SF

- Total rainfall per pipe = 40.2 gpm

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Drainage Pipe Design

- Using Perforated PVC Drainage Pipe:
  - 4" pipe at the base of the foundation walls
  - (2) 4" pipe beneath the slab-on-grade