Technical Report Two

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AE 481W-Senior Thesis
The Pennsylvania State University

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Executive Summary

Introduction:

The purpose of this report is to investigate the possible alternative floor systems for the Washingtonian Center. The four alternatives studied were non-composite steel, a girder slab, a post-tensioned flat plate, and a mild steel flat plate. The ultimate goal is to find which floor systems could potentially warrant more study to see if they could be used in a building redesign.

Building Description:

The Washingtonian Center is an eight story office building that is currently in the bidding process and has yet to have construction started on it. The building is an envelope and core design to allow for maximum flexibility of the leasable space. The majority of the mechanical equipment is located on the roof in a mechanical penthouse; this includes the cooling tower, the main air handling unit and a energy recovery system. The building sits on a site that is previously undeveloped. Development of the location is planned to include not only the first office building, but later a parking garage along with a second identical office building.

Conclusions from Technical Report Two:

After looking at and analyzing the four alternative floor systems, it is difficult to choose one that is definitely better than the rest. The decision really depends on what emphasis the owner and or architect puts on various factors. Some of these factors include the necessity to keep an open floor plan in the leasable space, the floor to floor heights and overall height of the building, and of course cost.

One of the first decisions that would need to be made is whether to use a concrete base floor design or a steel base floor design. Office buildings are routinely done in both so the occupancy doesn't dictate one material as more suitable than the other. If the designer's goal is to keep an open floor plan free of column, the clear choice is a steel structure. If the goal is to maximize leasable space within a given height restriction, a minimal floor to floor height is desirable and one of the concrete based systems would provide the best solution.

Between the two steel systems, there is really only one choice that makes much sense. While a non-composite floor is structurally possible, it doesn't seem to provide any real advantages over a composite system. The costs of the two systems are relatively close but the non-composite floor several inches deep than the already deep composite floor. It also weighs more than its composite counterpart which would require larger columns and footings. With these clear disadvantages of non-composite steel, it was concluded that it really doesn't make sense as a floor system for the Washingtonian Center.

The concrete based systems all require that the column grid be reworked to create short enough spans to allow their use. All three of these systems have the major advantage of providing a shallow floor. Once the analysis and design using the girder slab was complete, it became clear that this system just isn't feasible for this application. Pre-cast concrete systems are typically good for residential buildings where the live load is substantially less than the 100 pound per square foot being used to design this building. The girder slab system was selected because it provided a shallow floor, and was a composite system, therefore it was thought that it might provide the required strength. The analysis showed that the extreme compressive stress on the concrete was too great, and the system also deflected more than the allowable limit. The two flat plate designs both provided adequate strength and serviceability and both maintain a shallow floor depth. They also somewhat surprisingly came in as the two least expensive systems to implement, although that conclusion is questionable and would require a more in depth cost analysis than was performed in this report. Overall the investigation concluded that these could both be viable solutions for the Washingtonian Center.

The final recommendation from this floor system comparison would be that the best alternative system would be a post-tensioned concrete flat plate. This provides minimal floor to floor heights and is a very common system used in the Washington D.C. area. The cost of the system is also relatively low. The building location dictates that the seismic forces on the building aren't very high, therefore it isn't critical to keep the structure as light as possible. Additionally the soil provides adequate bearing capacity to make the additional weight that comes with this floor type not a problem. When compared to the mild steel flat plate, it makes more sense because of its thinner slab.

Structural Systems

Foundations:

The foundations for the Washingtonian Center consist of spread footings for the gravity columns with a combined mat footing for the lateral force resisting frames. Typically the exterior gravity columns are supported on 9' x 9' square footings that are 30" thick and have bottom reinforcing of #6 bars at eight inches in each direction. Interior gravity columns have a typical footing size of 11' x 11', 30" thick and reinforced with #8 at twelve inches on center. The lateral force resisting frames sit on a combined mat footing that is 40' x 36' and 4.5 feet thick. The mat footing has a base bottom reinforcing mat of #11 bars at nine inches in the long direction and #7 at twelve in the short direction. Additional steel is added around each column to take the increased moments. The top reinforcement consists of #7 at twelve inches in both directions with addition bars added around the columns. All the foundations are made from concrete having a compressive strength of 3000 psi.

Floor System:

The general floor system used is 3" 20 gage composite steel floor deck with 3.25" inch topping of light weight concrete with a compressive strength of 4000 psi. The floor is reinforced with 6" x 6"-W2.1 x W2.1 welded wire fabric placed 1" below the top of the concrete. This system is utilized for the 2nd – 8th floors. The ground floor is a slab on grade that is 5" thick and reinforced with 6" x 6"-W2.1 x W2.1 welded wire fabric. The slab on grade is poured on a 6" granular base. The steel deck floor system is supported on W21x44 beams spaced every 10' and spanning a distance of 45' on the exterior bays. The interior bays are supported by W14x22 spaced every 10' and spanning a distance of 20'. The girders supporting these beams are typically W14x22 spanning 20'.

Columns:

The columns in the building are spliced at the fourth floor and the seventh. All gravity columns in the building are either a W10 or W12 with sizes below the first splice point ranging from W10x49 to W12x96. Above the first splice location (floors 4,5 and 6) the columns range in size from W10x39 to W12x65. On the upper levels (floors 7, 8, the roof and mechanical penthouse) the columns range in size from W10x33 to W12x53. The un-braced length of the columns is the floor to floor height of 13'-4".

Lateral Frame:

The lateral force resisting system implemented in the Washingtonian Center is a series of concentrically braced chevron frames around the elevator cores need the center of the building. The frames span in both directions for a distance of 20'. The columns in the frames are spliced at the fourth and seventh levels and are W12x210 at the bottom, W12x106 at the middle levels and 12x65 at the upper floors. The beams in the frame are W18x50 and the chevron braces are W10x77.

Codes and Loads

Building Code:

International Building Code 2003 Edition

Steel Design:

American Institute of Steel Construction, LRFD Third Edition

Concrete Footings:

American Concrete Institute 2003 Edition

Building Design Loads:

American Society of Civil Engineers (ASCE-7) 2002 Edition

Loads used to design the current floor system:

Dead Loads:

Metal Deck and Concrete Topping for Strength	65psf
Floor mass for Seismic Design	85psf
Partition Allowance	25psf
Sprinkler Allowance	5psf

Live Loads:

Stairs and Exits	100psf
Elevator Machine Room	100psf
Offices	100psf
Public Spaces	100psf
Mechanical/Electrical Rooms	150psf
Roof	20psf

Loads used for the purposes of this report:

Dead Loads:

Self Weight	System Dependant: See weight table in the comparisons section
Partition Allowance	25psf
Sprinkler Allowance	5psf

Live Loads:

Stairs and Exits	100psf
Elevator Machine Room	100psf
Offices	100psf
Public Spaces	100psf
Mechanical/Electrical Rooms	150psf

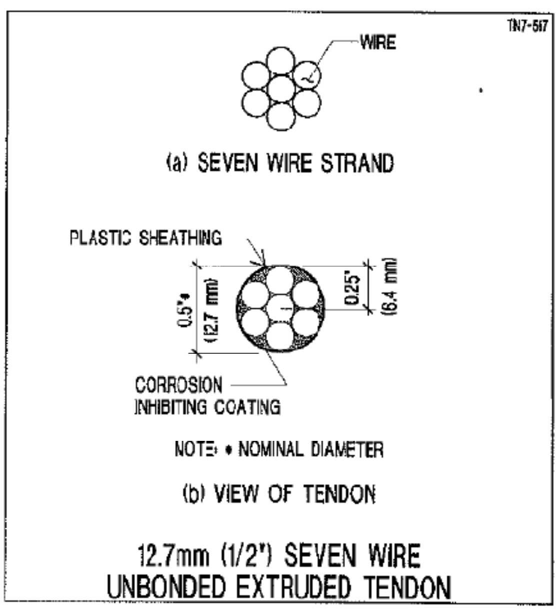
Floor System Descriptions

Composite Steel

A composite steel floor system was used in the original design of the building and will serve as a comparison for the following alternative designs. The floor system used is 3” 20 gage composite steel floor deck with 3.25” inch topping of light weight concrete with a compressive strength of 4000 psi. Shear studs were placed along the span of the beams at a spacing (determined by Ram Structural Systems) required to develop composite action to resist the applied loads. The framing plan with beam and girder sizes for the composite floor can be found in the appendix.

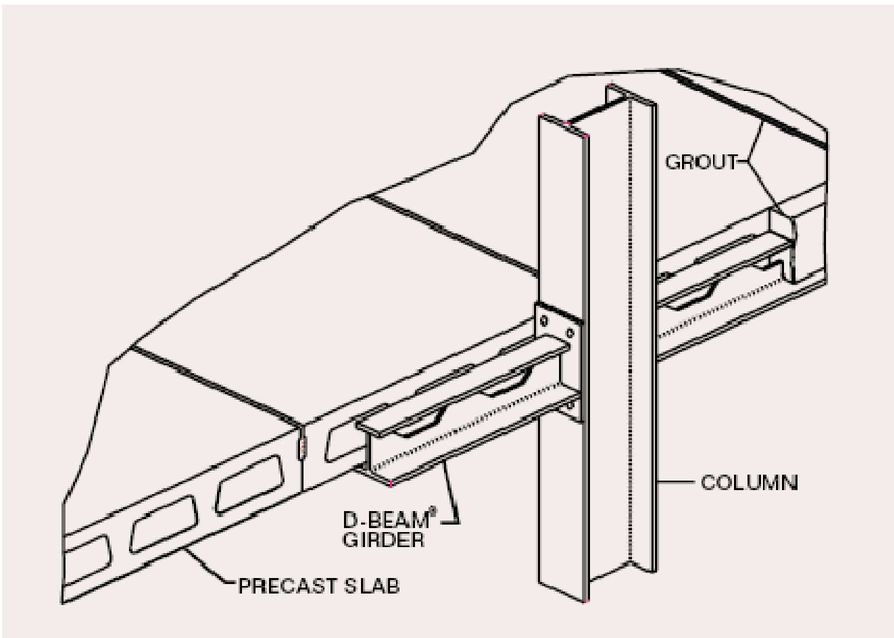
Two-Way Post-Tensioned Flat Plate:

To use this floor system a reworking of the column grid was necessary. The span lengths that were used in the original steel design were far to great to make it possible to use a concrete system of almost any kind. To remedy this, I added additional columns along grid lines two and five bringing the typical bay sizes to a very reasonable 20’ x 20’. Please refer to the appendix for a diagram of the column layout used for this design. For the design of the floor system, Ram Concept was used to layout and design the post-tensioning. Concrete with a compressive strength of 5000psi was used. The design process began by selecting the span of the girders in the original design as the direction that the banded tendons would run and the beam span direction of the distributed tendons. The decision was made to use ½” unbonded tendons made up of seven strands (see figure below). The initial number of tendons required was selected based on the required pre-compression of 150 psi. The banded tendons were then laid out with the required number of cables needed to achieve the pre-compression. The distributed tendons were laid out using a 4’ spacing, while the pre-compression again dictated that there would be three tendons in each tendon path. Once all spans were placed 75% of the dead load was balanced in each direction by changing the profile of the tendons in each bay. The tendons profiles were done so that the cables had the same elevation of seven inches over each column (determined from the protection of the tendon requirements of ACI 138-05 and a slab depth of 8”), and the balancing loading requirements were achieved by changing the drape at the mid span of the tendons. After the design was complete, it was concluded that an eight inch flat plate systems would be adequate to support the loads. A full summary of the design including the tendon layouts and profiles, balancing load percentages for each bay, and mild steel required in the design can be found in the appendix of this report.



Girder Slab System:

The Girder-Slab system is a unique and relatively new floor system. It utilizes a hybrid of steel and precast concrete to create a monolithic structural slab assembly. The concrete and steel together develop composite action that allows it to carry substantial loading. A specially created steel beam with a wide bottom flange is used to support the precast concrete panels. This allows for much lower floor to floor heights. The entire assemble is grouted together once it is in place, by filling the slab cores and encapsulating the steel beam.



Design:

A typical bay size of 20'x20' was selected to be used in the design of the girder slab floor system (please refer to the appendix for the column grid and framing associated with this design). The grouting was done using a compressive strength of 4000psi. Using a design spread sheet provided by the manufacturer of the girder slab product, a steel D-Beam of the designation DB8x42 was selected for use in the floor system. A precast pre-stressed hollow core concrete plan was then selected from the Nitterhouse product catalog that was able to withstand the required factored loading. The final result was a total depth of just of 8" for the floor system.

Two-Way Mild Steel Flat Plate:

To make this a feasible floor system required the use of the modified column grid that both the post-tensioned floor and the girder slab floor utilized. Once the column layout was determined PCA slab was used to design the frame along grid line B. This required analyzing the frame in both directions by making different models for each. The design resulted in a 10" concrete slab with a compressive strength of 4000 psi. The rebar requirements and details for a typical bay in that frame can be found in the appendix. A check of the punching shear and panel zone shear for a column in the slab can also be found in the appendix.

Non-Composite Steel:

This is a simple variation of the composite floor system that the building was originally designed using. The column grid, (refer to the appendix) and the beam and girder framing were all kept the same as in the original design. Ram Structural Systems was used to model the entire building and to design the gravity frame of the structure (this was done for technical report 1 and then modified to find the non-composite floor design). The goal of this investigation was to see if the composite action developed between the floor and the beams supporting it caused a significant savings in the sizes of the beams. The results showed that there were significant changes in beam sizes. The typical beam size jumped from a W21x44 to a W24x68. It should be noted however that the non-composite system was designed using the loads that were developed in technical report 1 which aren't necessarily the same loads that the composite floor system was design for. A more accurate comparison can be made using the composite framing design that was done as a check of the floor system in technical report 1 which was also designed using the same loads. In that design the typical beam size was found to be a W24x55 which is two sizes smaller then that size found with non-composite deck.

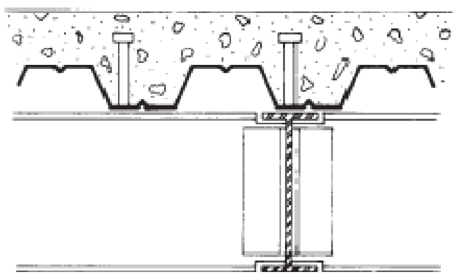
Floor System Designs

Note: This Section Provides a brief overview of the designs of each of the floor systems. Please Refer to the appendix for the complete design.

Composite Steel

Material Properties: f'_c=4000psi f_y=60,000psi

Typical Floor Section:

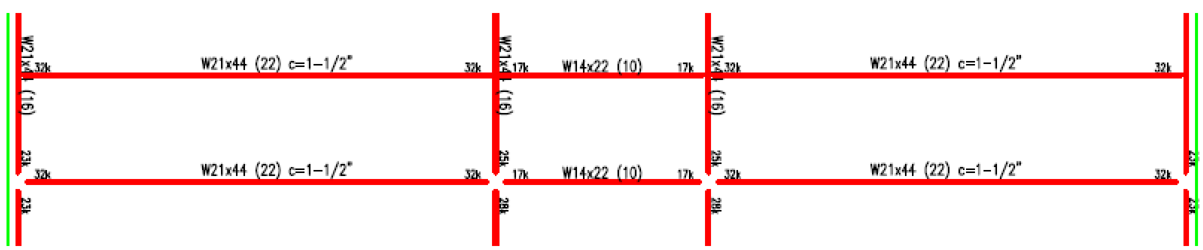


Typical Member Sizes:

Beams: W21x41 Spanning 45 feet

Girders: W21x41 Spanning 20 feet

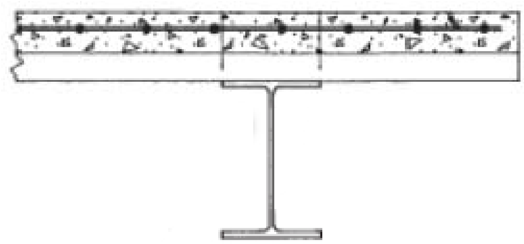
Typical Bay:



Non-Composite Steel

Material Properties: f'_c=4000psi f_y=60,000psi

Typical Section:

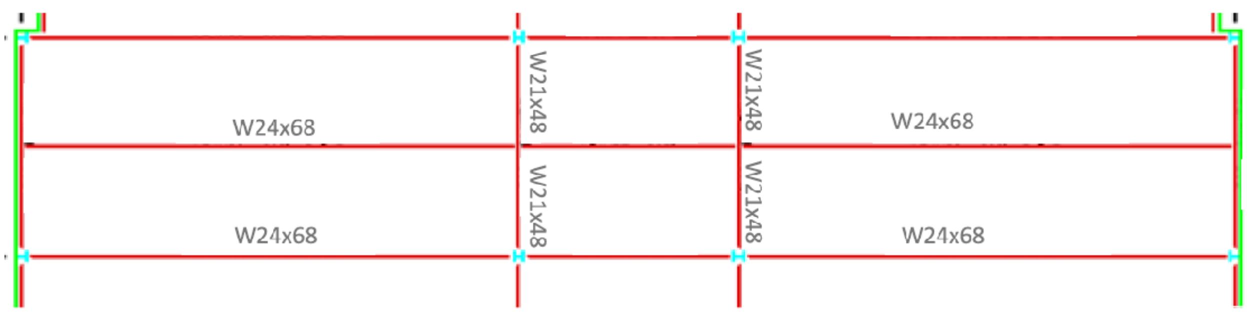


Typical Framing:

Beams: W24x68 Spanning 45 Feet

Girders: W21x48 Spanning 20 Feet

Typical Bay:

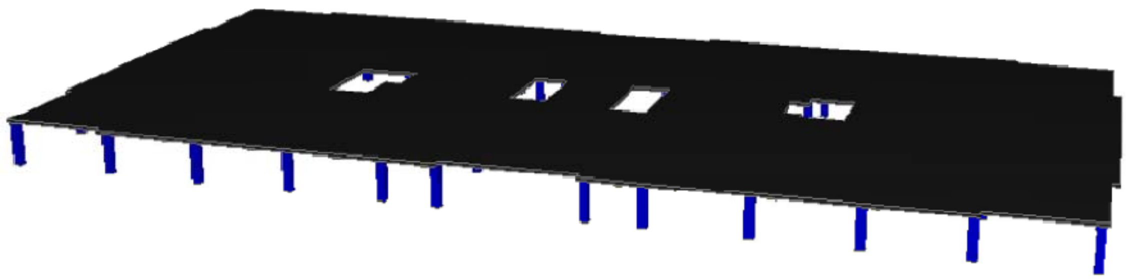


Two Way Post-Tensioned Flat Plate

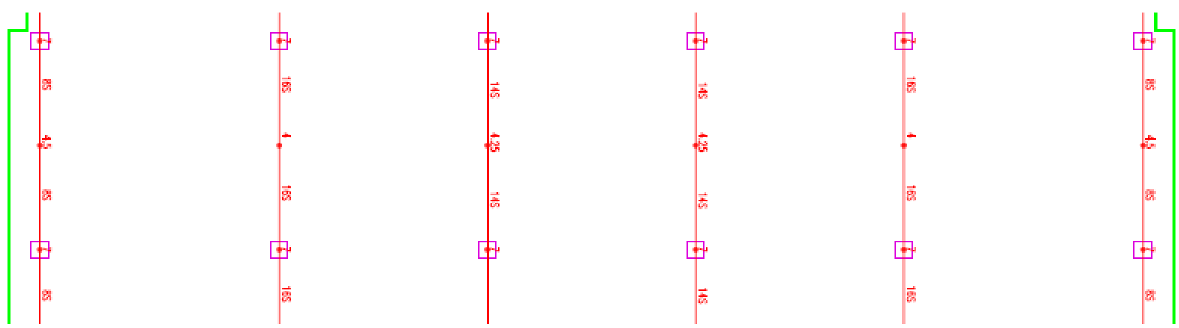
Typical Bay Sizes: 20'x20' using the alternative column grid (refer to appendix)

Material Properties: f'_c=4000psi f_y=60,000psi ½" Un-bonded seven strand tendon

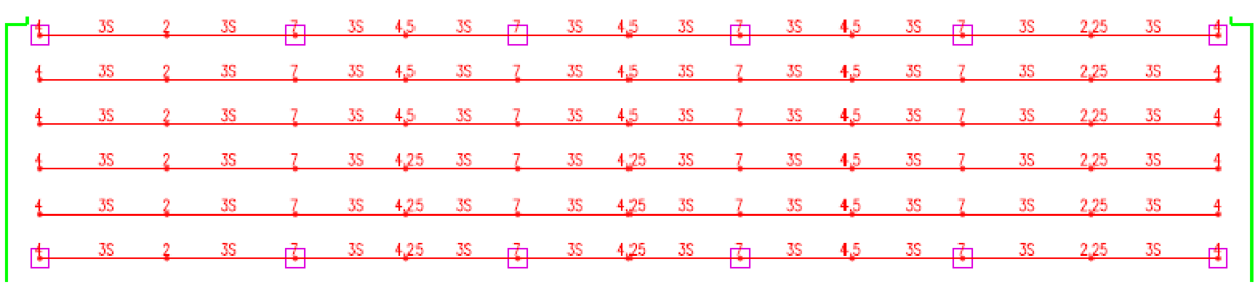
Column Sizes: 20" x 20"



Typical Bay Banded Tendon Layout: Refer to the appendix for the entire floor layout



Typical Bay Distributed Tendon Layout: Refer to the appendix for the entire floor layout



Punching Shear Check

Two-Way Post Tensioned Slab

Loading:

Dead=	125	psf
Live=	100	psf
Wu=	310	psf

Column:

Width=	20	inches
Depth=	20	inches

Slab:

f'c=	4000	psi
Thickness=	10	inches
Span N-S=	20	feet
Span E-W=	20	feet

Shear:

Vc=	303.5787
phi*Vc=	227.684
Vu=	122.0625

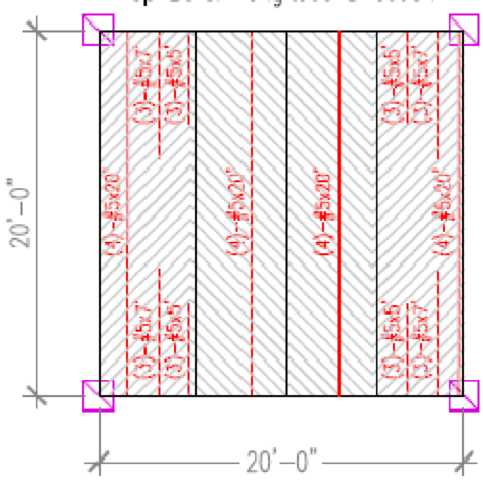
Two Way Mild Steel Flat Plate

Material Properties: f'_c=4000psi f_y=60,000psi

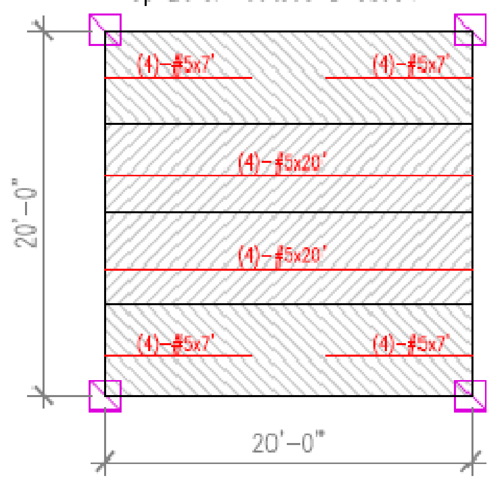
Column Grid: Alternative Grid (refer to the appendix for a visual representation of this arrangement)

Column Sizes: 20" x 20"

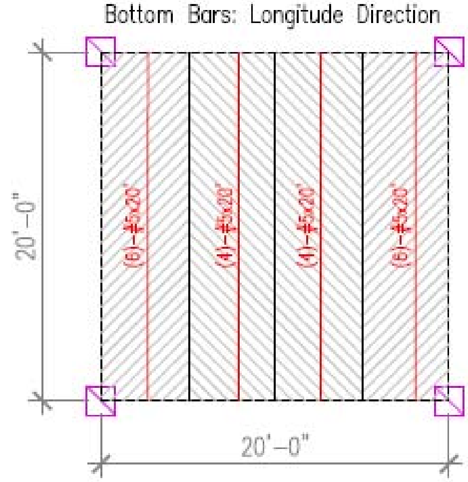
Top Bars: Longitude Direction



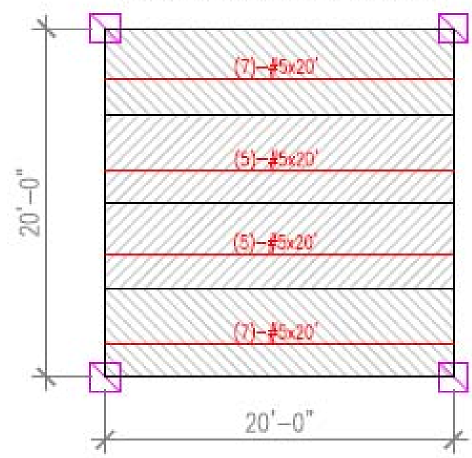
Top Bars: Latitude Direction



Bottom Bars: Longitude Direction



Bottom Bars: Latitude Direction



Punching Shear Check

Two-Way Mild Steel Slab

Loading:

Dead=	125	psf
Live=	100	psf
Wu=	310	psf

Column:

Width=	20	inches
Depth=	20	inches

Slab:

f'c=	4000	psi
Thickness=	10	inches
Span N-S=	20	feet
Span E-W=	20	feet

Shear:

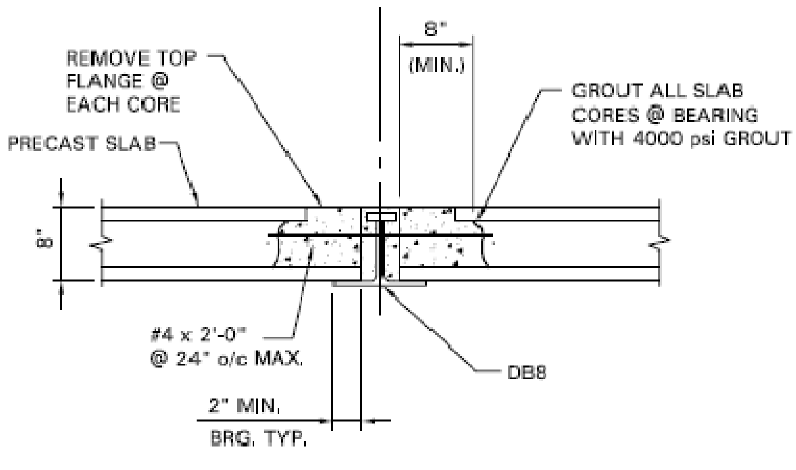
Vc=	303.5787
phi*Vc=	227.684
Vu=	122.0625

Girder Slab

Typical Bay: 20'x 20'

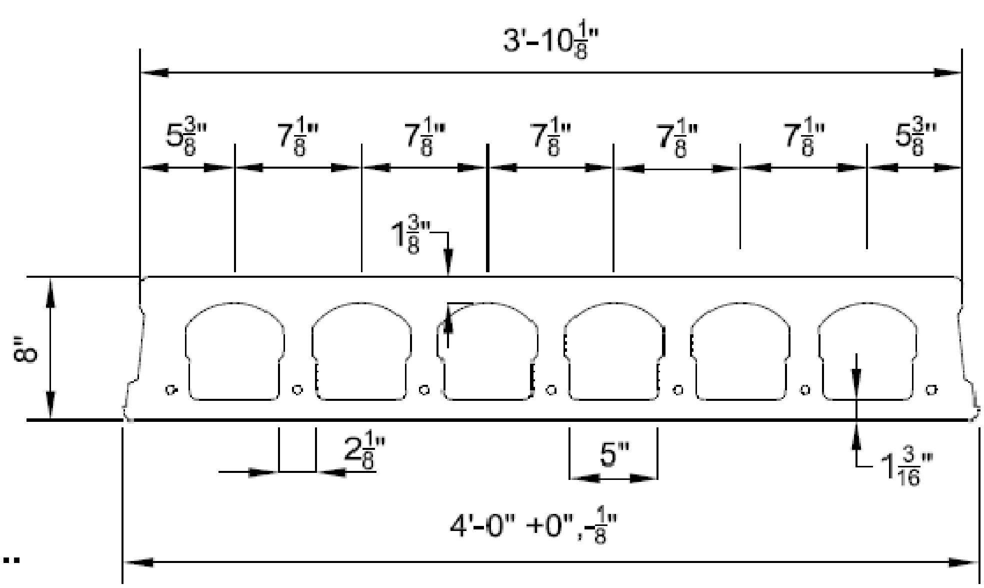
Layout: Hollow Core Precast Panels spanning 20 feet, 4 feet wide, 8 inches deep

Typical Section:



TYPICAL SECTION: 8" GIRDER-SLAB® SYSTEM

Pre-Cast Hollow Core Panel Used from Nitterhouse Concrete Products



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Design Calculations: From Manufacturer's Design Spread Sheet

Design Information

Dead Load =	60	psf
Partition Load =	25	psf
Live Load =	100	psf
Topping Load =	0	psf
DB Span =	20	ft
Plank Span =	20	ft
Grout f'c =	4000	psi
Allowable Δ_{LL} = L /	360	
Allowable Δ_{LL} =	0.67	in

DB Properties

DB Size ------------> DB 9 x 46

Steel Section			**Transformed Section**		
I_s =	195	in^4	**I_t =**	356	in^4
S_t =	33.7	in^3	**S_t =**	68.6	in^3
S_b =	50.8	in^3	**S_b =**	80.6	in^3
M_{scap} =	84.0	ft-k			
t_w =	0.375	in			
b =	5.75	in			

Live Load Reduction (IBC 00/03/06)

Include LLR ☐		(Check for Yes)			
% Reduction =	N/A				
Reduced Load =	N/A				

Initial Load - Precomposite

M_{DL} =	60.0 ft-k		**<**	84.0 ft-k	**OK**
Δ_{DL} =	0.76 in				
Δ Ratio = L /	314				
Camber D-Beam ☑		(Check for Yes)			
D-Beam Camber	0	in			

Total Load - Composite

M_{sup} =	125.0 ft-k				
M_{TL} =	185.0 ft-k				
S_{REQ} =	74.0 in^3		**>**	68.6 in^3	**NO GOOD**
Δ_{SUP} =	0.87 in		**>**	0.67 in	**NO GOOD**
Δ_{TOT} =	1.64 in		= **L/**	147	

Superimposed Compressive Stress on Concrete

N value =	8.04				
S_{tc} =	552 in^3				
f_c =	2.72 ksi				
F_c =	1.80 ksi		**<**	2.72 ksi	**NO GOOD**

Bottom Flange Tension Stress (Total Load)

f_b =	32.8 ksi				
F_b =	45 ksi		**>**	32.8 ksi	**OK**

Shear Check

Total Load =	185 psf				
w =	3.70 klf				
R =	37.0 k				
f_v =	17.2 ksi				
Fv =	20 ksi		**>**	17.2 ksi	**OK**

Floor System Comparisons

Vibration:

The analysis of floor vibrations is often something that gets over looked during the design process. Vibrations due to human walking excitation are of particular concern for office buildings in which the occupants are stationary and therefore have a higher perception of vibration. For the purposes of this report, the floor systems under consideration will be evaluated based on several criteria. For the steel systems, the AISC Design Guide 11 procedure for walking excitation will be used. The procedure for checking vibrations in concrete floor systems isn't as clear or well researched as it is for steel. Therefore to check the concrete floors I used a process that was published by the American Concrete Institute in 1979 in a book entitled, Vibrations of Concrete Structures. The book details a procedure for determining the fundamental frequency of a floor system. I used this process to find the fundamental frequency of the floors and then used the equation given by AISC to find the peak acceleration as a percentage of gravity, then plotted both points on the graph of acceptability given by AISC. This combination of the two processes is applicable because the floor material only affects the calculation of the fundamental frequency of the floor. To determine the acceptability of the non-composite floor and the girder slab system, a simple comparison of the effective moments of inertias of these systems to the effective moment of inertia of the composite system will be made. If their inertias are greater than the inertia composite floor, they are unlikely to be susceptible to floor vibrations.

Acceptability of the Composite Floor System Used:

The AISC Design Guide 11 was used to evaluate the current floor system. The Criterion states that the floor system is satisfactory if the peak acceleration, a_p due to walking excitation as a fraction of the acceleration of gravity doesn't exceed the acceleration limit given in the graph below. The peak acceleration is determined from the following equation.

$$\frac{a_p}{g} = \frac{P_o \exp(-0.35 f_n)}{\beta W}$$

P_o=a constant force representing the excitation

B=modal damping ratio, used as .03 for this excercise

The above two factors are found from the table given below

g=32.2

F_n=fundamental natural frequency of the beam, as determined by Ram Structural System to be 3.86 hz

W=effective weight supported by the beam, used as 21,000 lbs over the 45' span of a typical beam determined from the dead weight

Using these values the ap/g ratio was found to be: 0.0267

When plotted on the acceptable limits graph below the floor system is determined to be acceptable.

Table 4.1
Recommended Values of Parameters in Equation (4.1) and a_o/g Limits

	Constant Force P_o	Damping Ratio β	Acceleration Limit $a_o/g \times 100\%$
Offices, Residences, Churches	0.29 kN (65 lb)	0.02–0.05*	0.5%
Shopping Malls	0.29 kN (65 lb)	0.02	1.5%
Footbridges—Indoor	0.41 kN (92 lb)	0.01	1.5%
Footbridges—Outdoor	0.41 kN (92 lb)	0.01	5.0%

* 0.02 for floors with few non-structural components (ceilings, ducts, partitions, etc.) as can occur in open work areas and churches,
0.03 for floors with non-structural components and furnishings, but with only small demountable partitions, typical of many modular office areas,
0.05 for full height partitions between floors.

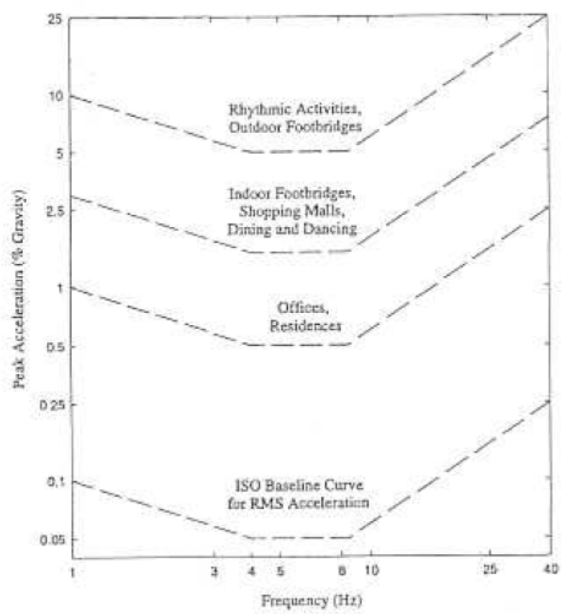


Fig. 2.1 Recommended peak acceleration for human comfort for vibrations due to human activities (Allen and Murray, 1993; ISO 2631-2: 1989).

Evaluating the Alternative Floor Systems for Vibration

Concrete Analysis Process:

As outlined above the fundamental natural frequency of the floor systems were determined by a procedure detail in a 1979 ACI publication. The Equations that were used are shown as excerpts from that text below.

Fig. 2 shows how the natural frequency of reinforced concrete can be determined. The details were developed using following frequency expressions

$$f = \frac{\pi}{2}\left(\frac{1}{\ell_x^2}+\frac{1}{\ell_y^2}\right)\sqrt{\frac{D}{\rho t}} \qquad (2)$$

where,

$$D = E\,t^4/12(1-\nu^2) \qquad (3)$$

The natural frequencies were then used in the AISC Design Guide 11 procedure. The results are shown on the table below.

<u>Two Way Post-Tensioned Slab:</u>

$p_{avg.}$=	0.002	
F'_c=	5000	psi
E=	4030.51	ksi
Slab Depth=	8	inches
Possion's Ratio=	0.2	
D=	1433070	$k*in^2$
L_x=	240	inches
L_y=	120	inches
Fn=	1.29	hz
W=	20000	lbs
P_o=	65	lbs (Table 4.1, above)
B=	0.03	(Damping Ratio, Table 4.1, above)
a_p=	2.22	
a_p/g=	0.069	
Acceptable:	Yes	

Mild Steel Slab

$p_{avg.}$=	0.002	
F'_c=	4000	psi
E=	3605.00	ksi
Slab Depth=	10	inches
Possion's Ratio=	0.2	
D=	3129337	$k*in^2$
L_x=	240	inches
L_y=	120	inches
Fn=	1.70	hz
W=	25000	lbs
P_o=	65	lbs (Table 4.1, above)
B=	0.03	(Damping Ratio, Table 4.1, above)
a_p=	1.54	
a_p/g=	0.048	
Acceptable:	Yes	

Using the AISC Steel Construction Manual's Composite beam tables, it was found that the current effective moment of inertia of the slab, deck, and beam assembly is 2370 in^4 . The composite floor system had beam spaced at 10' on center so that will be used as the width in calculating the other inertias. The calculations for the other floor types are described below. Comparing their effective moments of inertia with the current system it seems as if none of the alternatives will have a vibration problem either.

Effective Moment of Inertia

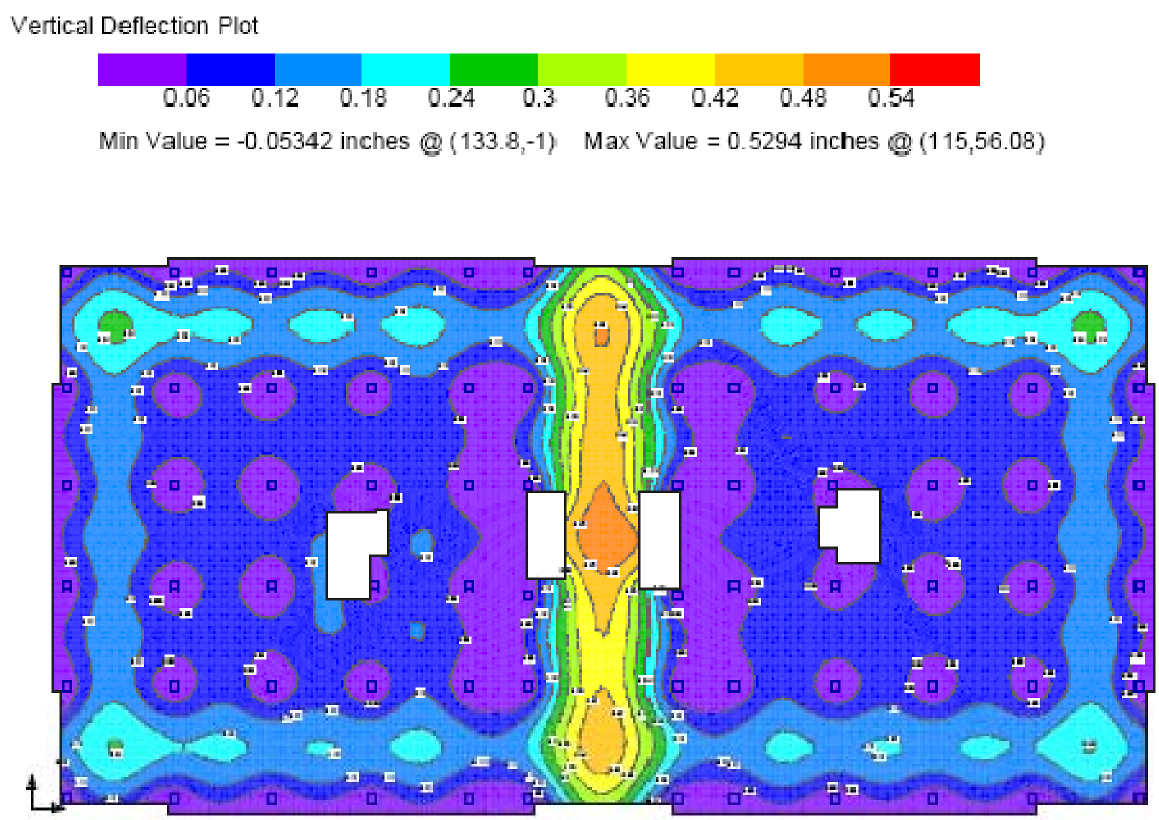
Non-Composite Steel		
I_{steel}=	1830	in^4
$I_{concrete}$=	120	in^4
Inertia=	2900	in^4
Girder Slab		
I_{steel}=	291	in^4
$I_{precast}$=	1640	in^4
$I_{precast-10'}$=	4100	in^4
Inertia=	4391	in^4

Deflection:

Even though many floor systems can deflect a large amount and still be structurally sound from a strength stand point, deflections need to be limited to make the floor comfortable to for the occupants. The generally accept deflection criteria for an office building floor systems is the span length over 360. This will be used to evaluate each of the floor systems under consideration. Because the floors were designed using different materials and methods, the process for determining their deflections will not all be the same. Outlined below is the method for determining the deflections of each floor type and the results from the analysis.

Post-Tensioned Two Way Flat Plate

Ram concept was used to design this floor plate, and it conveniently includes in its analysis the deflection of the floor. The plot of the deflections is included below. For a larger version of the plot please refer to the appendix.



From the plot it can be seen that the maximum deflection in the floor is 0.54 inches, which is within the L/360 limit for a twenty foot span.

Two-Way Mild Steel Flat Plat

The ACI Code gives the minimum thickness of a two way slab to ensure that deflections of the slab will not be a problem. The table is reproduced below. It can be seen that for a flat plate the thickness must exceed L/33 for interior panels and L/30 for exterior panels using reinforcement of fy=60,000 psi. This converts to a required thickness of 8", which is less than the design thickness of 10".

TABLE 9.5(c)—MINIMUM THICKNESS OF SLABS WITHOUT INTERIOR BEAMS*

	Without drop panels‡			With drop panels‡		
	Exterior panels		Interior panels	Exterior panels		Interior panels
f_y, psi†	Without edge beams	With edge beams§		Without edge beams	With edge beams§	
40,000	$\frac{\ell_n}{33}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{40}$	$\frac{\ell_n}{40}$
60,000	$\frac{\ell_n}{30}$	$\frac{\ell_n}{33}$	$\frac{\ell_n}{33}$	$\frac{\ell_n}{33}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{36}$
75,000	$\frac{\ell_n}{28}$	$\frac{\ell_n}{31}$	$\frac{\ell_n}{31}$	$\frac{\ell_n}{31}$	$\frac{\ell_n}{34}$	$\frac{\ell_n}{34}$

Girder Slab

The manufacturers of the girder slab publish an excel sheet was used to do the design of the system. The user inputs the loading, spans and grout strength and it calculates the strength of the system along with the deflections. This system doesn't meet the L/360 requirement of a service deflection of less than 0.67 inches. The actual deflection comes to 0.87 inches. Please refer to the appendix for the spread sheet calculations.

Non-Composite Steel

The deflection for the non-composite steel floor system was calculated by Ram Structural Systems as part of the design and analysis. A typical beam size of W24x68 spanning 45 feet was found to deflect 1.53 inches. This is slightly over the 1.5 inch limit and thus required a half inch camber in many of the beams spanning this far. With the camber in the beams the deflection limits are within the acceptable range.

Cost:

The cost of a particular system is often a deciding factor when determining which should be used in a design. The actual cost is often something that is difficult to predict accurately and can fluctuate greatly from region to region. A simple but effective method used estimate the cost of the floor systems under consideration is the RSMeans Building Construction Data 2008 and the RSMeans Assemblies Cost Data 2007. The following is the estimated cost of each floor type based on the RSMeans values.

Post-Tensioned Slab

Cast-in-Place Flat Plate			
	Bay Size:	20'x20'	
	Depth:	8	inches
	F'c:	4000	psi
	Floor Area:	24,500	sf
	Assembly Cost:	$13.50	/sf
Tendon Cost (material and placement)			
	Material:	17960	lbs
	Unit Cost:	$2.58	/lb
	Total Cost:	$377,086.80	/Floor

Two Way Mild Slab

Cast-in-Place Flat Plate			
	Bay Size:	20'x20'	
	Depth:	10	inches
	F'c:	4000	psi
	Floor Area:	24,500	sf
	Assembly Cost:	$13.50	/sf
	Total Cost:	$330,750.00	/Floor

Non-Composite Steel

Steel Framing (materials and placement)

Bay Size:	20'x20'	
Load:	250	psf
Floor Area	8910	sf
Unit Cost:	$16.80	/sf
Bay Size:	45'x20'	
Load:	250	psf
Floor Area	15590	sf
Unit Cost:	$21.53	/sf

Decking and Fill

Load:	250	psf
Span:	10	ft
Unit Cost:	$6.69	/sf
Total Cost:	$649,245.70	/Floor

Composite Steel

Assembly

Bay Size:	20'x20'	
Load:	250	psf
Floor Area	8910	sf
Unit Cost:	$20.70	/sf
Bay Size:	45'x20'	
Load:	250	psf
Floor Area	15590	sf
Unit Cost:	$25.85	/sf
Total Cost:	$587,438.50	/Floor

Girder Slab

Pre-Cast Panel			
	Span:	20	ft
	Depth:	8	inches
	Unit Cost:	$9.51	/sf
Steel:			
	Bay Size:	20'x20'	
	Depth:	8	inches
	Load:	250	psf
	Unit Cost:	$16.80	
	Total Cost:	$644,595.00	/Floor

Total Cost Discussion:

From the RSMeans estimation of the floor system costs, there appear to be significant differences between the concrete and steel based designs. The steel least expensive steel base design was 55% most costly then the most expensive concrete based design. It should be noted that these numbers are rough estimates but they do give a reasonable idea as to the cost of the five systems.

Fire Protection:

The Washingtonian Center requires that a two hour fire rating for all floor assemblies. This can have a large influence on the choice of floors used because fire proofing can add significant cost and labor to some floor types. The two concrete flat plate systems have sufficient concrete cover that they require no additional protection to achieve the two hour rating. The girder slab system is a hybrid combination of steel and concrete that is achieves its composite action by covering the steel beam with grout and filling the pre-cast hollow cores as well. This methodology has an additional benefit in that it also provides fire protection to the steel beams, thus eliminating the need for additional fire proofing. The composite and non-composite steel floor systems will both need additional fire proofing on the steel members to get an assemblies rating of two hours.

Total Depth of the Floor System

There are several benefits to limiting the overall depth of a floor within a building. The first is that it requires a lower floor to floor height and thus reduces the overall building height. In some cases where a strict limit on the building height is imposed, limiting the floor to floor heights becomes a crucial issue. Another issue that is of particular importance to the architects is that the space taken up by the floor structure is taken out of the architectural interior space of the building. This can create an unpleasant experience of the space in some cases and should be avoided if possible. Below is a chart with the depths of the various floor systems. Clearly there is a large difference between the steel based systems and the concrete based systems. It should also be noted that these numbers do not include any space allowance or other consideration for the mechanical and electrical systems to be installed. The steel systems could probably incorporate these ducts without any additional space, while the concrete systems would need to add additional space to the total depth of the floor to incorporate the other equipment that needs to be installed.

System	Total Depth
Composite Steel	28 inches
Non-Composite Steel	30 inches
PT Flat Plate	8 inches
Mild Steel Flat Plate	10 inches
Girder Slab	8 inches

Weight of the Floor System

The weight of a floor is a factor that influences the performance of the floor itself and also affects the entire structure. Vibrations in a floor are directly related to the weight of the system, the more weight a member is supporting, the lower its acceleration will be and thus, the less vibration will be perceivable. With that said it generally isn't a good idea to optimize the vibration performance of a floor system by increasing its weight, there are other more effective ways to mitigate vibrations. Reasons to choose a light floor include the fact that the more the floor weighs the larger the columns and beams supporting the floor will have to be, which ultimately adds more loading to the foundations. In short, a heavy floor requires a much heavier structure to support it. Additionally seismic loading is also a direct function of the weight of the building. This is another reason why the weight of the floor should be kept to a minimum. Below is a table comparing the approximate weight of each floor system being evaluated.

Floor Type	Approximate Weight (psf)
Composite Steel	65
Non-Composite Steel	70
Girder Slab	115
Post-Tensioned Slab	100
Mild Steel Slab	125

Comparison Chart

Floor System	Vibration	Deflection	Cost	Fire Protection	Depth (inches)	Weight (psf)	Feasible
Composite Steel	Acceptable	Acceptable	$587,000	Spay-on-Proofing	28	65	Yes
Non-Composite Steel	Acceptable	Acceptable	$650,000	Spay-on-Proofing	30	70	No
Post-Tensioned Flat Plate	Acceptable	Acceptable	$377,000	Ok	8	100	Yes
Mild Steel Flat Plate	Acceptable	Acceptable	$330,750	Ok	10	125	Yes
Girder Slab System	Acceptable	Acceptable	$645,000	Ok	8	115	No

Floor Comparison Summary

Post-Tensioned Flat Plate

Advantages:

- Low floor to floor heights
- Unlikely to have vibration problems
- Common construction technique in the Washington D.C area
- Cost effective alternative to composite steel
- Doesn't require fire proofing
- Acceptable deflection performance

Disadvantages:

- Increased weight of the floor, resulting in larger seismic base shear and foundations
- Requires smaller bay sizes, placing columns in the middle of the leasable space
- Careful inspection of tendon placement and drape required

Mild Steel Flat Plate

Advantages:

- Relatively low floor to floor heights
- Unlikely to have vibration problems
- Doesn't require post-tensioning
- Doesn't require fire proofing
- Acceptable deflection performance
- Low cost

Disadvantages:

- Very heavy floor system
- Requires smaller bay size

Girder Slab

Note: The design section of this report has shown that the girder slab system is not a feasible floor system in this application. The advantages and disadvantages listed below are being reported as considerations in cases where it would actually work.

Advantages:

- Shallow floor system
- No fire proofing required

Disadvantages:

- Prone to deflections
- High Cost
- Short Spans
- Heavy
- Not a common system used, would require strict inspections to ensure proper construction

Composite Steel

Advantages:

- Long Spans
- Light Weight
- Very common floor system

Disadvantages:

- High Cost
- Requires spray on fire proofing for the steel beams and girders
- Deep Floor depths
- Could be susceptible to floor vibrations depending on the damping provided by the finishes within the space

Non-Composite Steel

Advantages:

- Long spans
- Light weight

Disadvantages:

- High cost
- Very deep floors
- Spray on fire proofing required

Report Summary

Upon the conclusion of the floor system investigation it is clear that there are possible alternatives to the composite steel floor that was used. The two that are possible and make sense for the building are the two concrete flat plate designs. They offer many advantages over the composite steel system and have few disadvantages. These two systems could be considered further for a redesign of the buildings. On the other hand the non-composite steel floor just doesn't make sense for this application. Everything it does, the composite floor system does better, and therefore no further investigation into this floor type will be needed. The girder slab system simple doesn't work structurally for this building. The loading is just too great to the pre-cast composite floor to resist, making it clearly not worthy of anymore consideration.

Appendix

Column Layouts: This diagram depicts the columns grid required for the different floor types. Column Layout 1 is used for the steel systems while column layout 2 is used for the concrete based systems.

Composite Floor Framing: This is the layout of the beams and girders that was used in the current design.

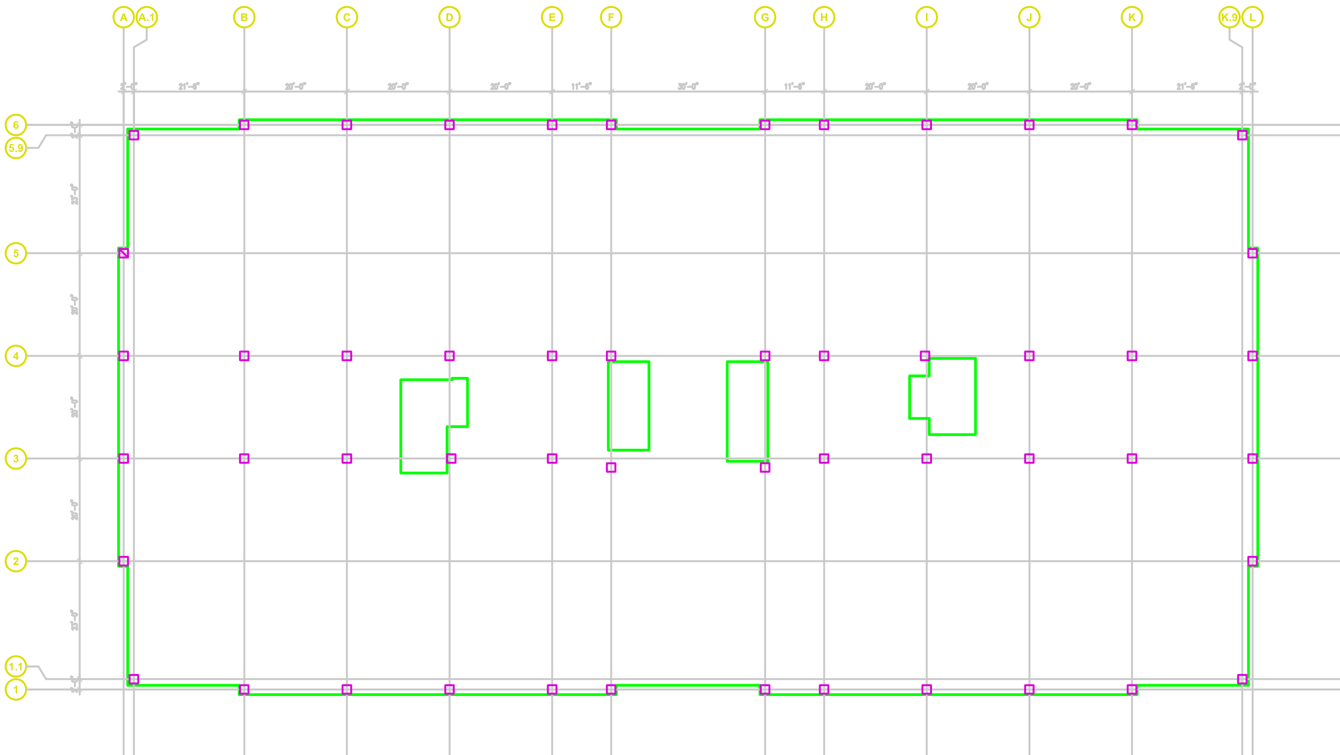
Non-Composite Framing: This is the layout of the beams and girders that was designed for this floor system.

Girder Slab Framing: This is the layout of the pre-cast hollow core planks and the steel beams supporting them for this system.

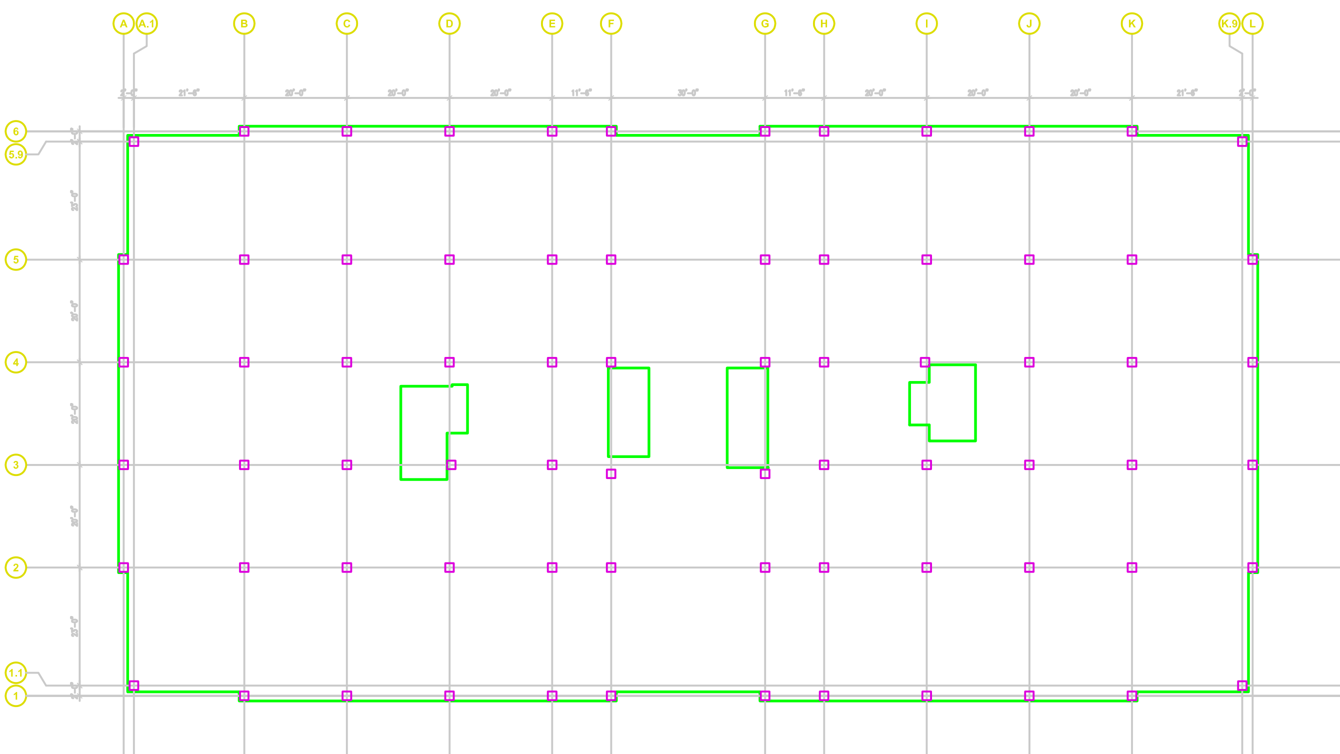
Post-Tensioned Flat Plate Design: This section includes the details of the design done in Ram Concept.

Mild Steel Flat Plate Design: This section includes the typical bay reinforcement design.

Column Layout 1

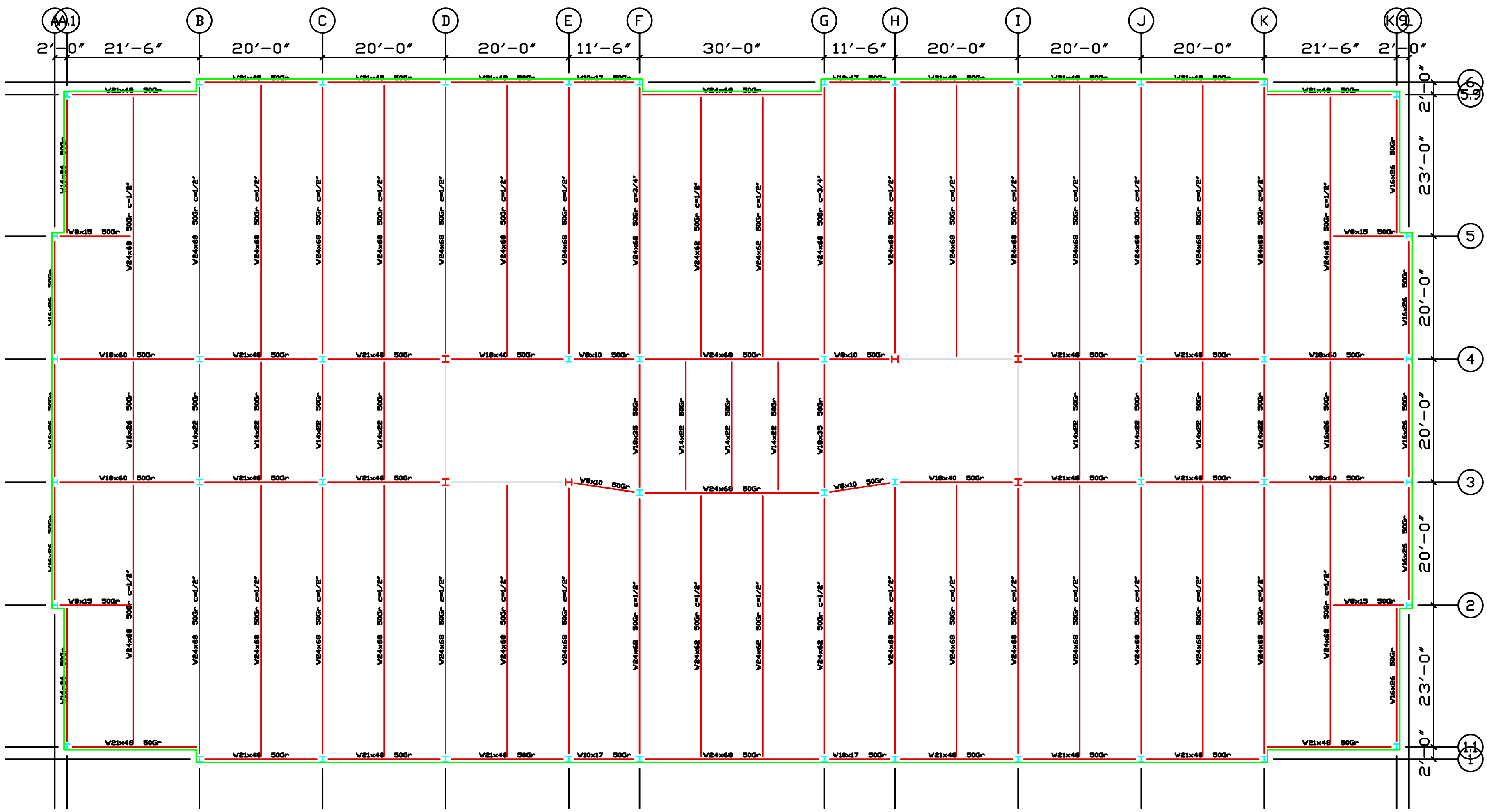


Column Layout 2



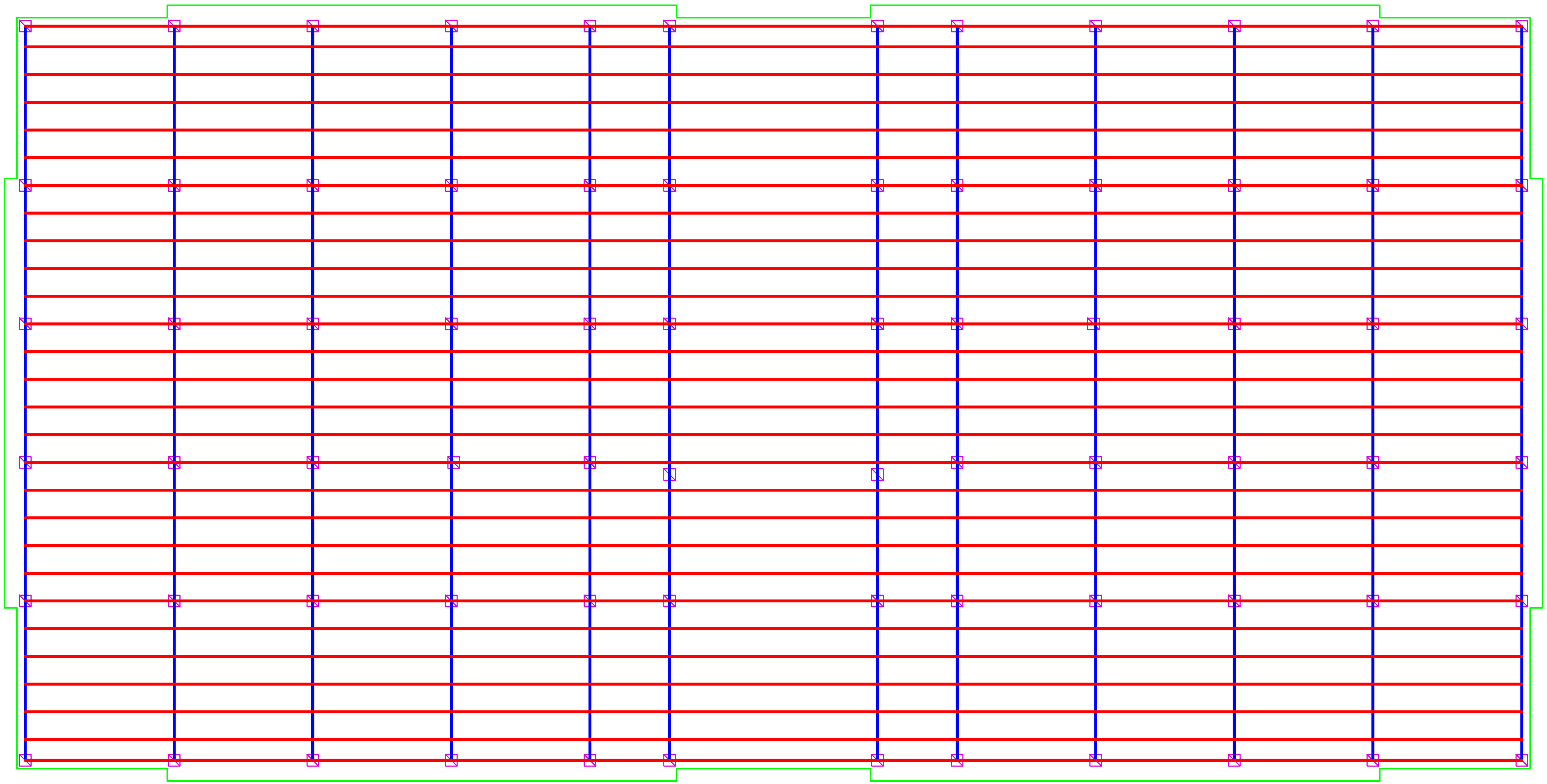
Current Framing Design

Typical Floor Framing Plan: Non-Composite Floor Slab



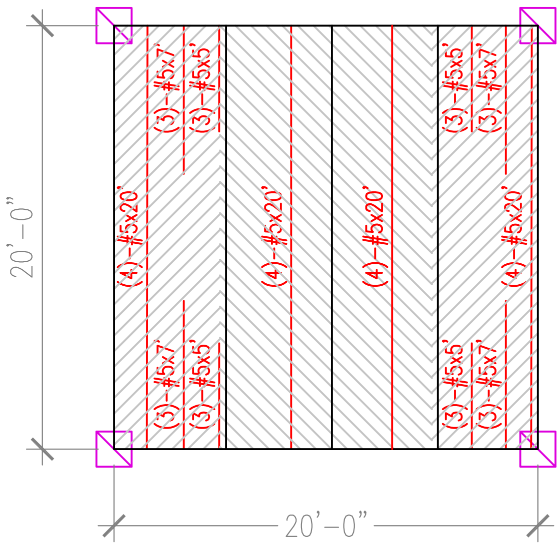
Grider Slab Pre-Cast Layout

Note: The Steel Beams are Represented in Blue

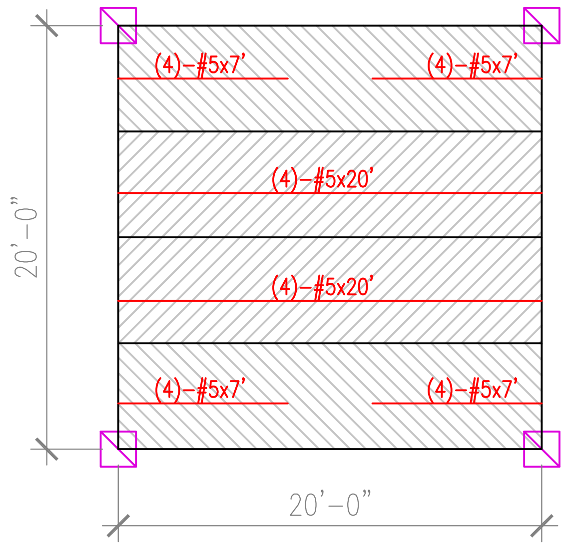


Typical Bay: Two-Way Mild Steel Flat Plate Reinforcement

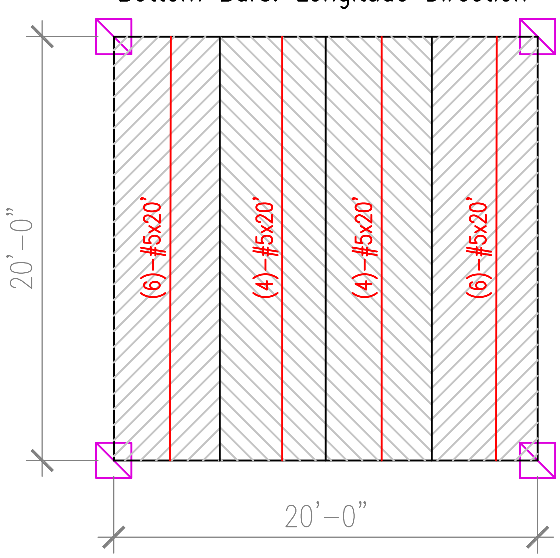
Top Bars: Longitude Direction



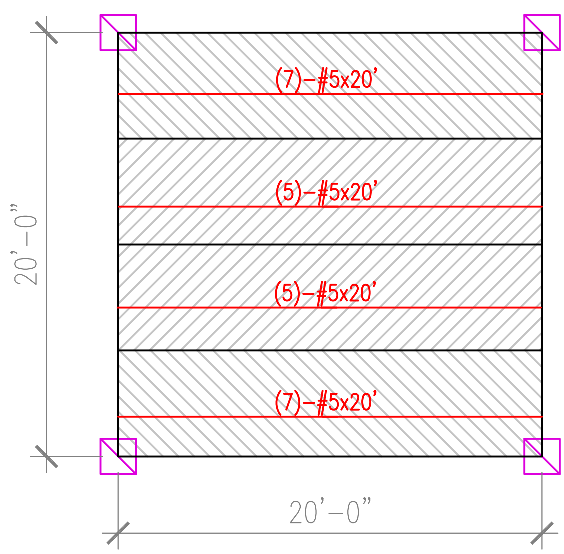
Top Bars: Latitude Direction



Bottom Bars: Longitude Direction

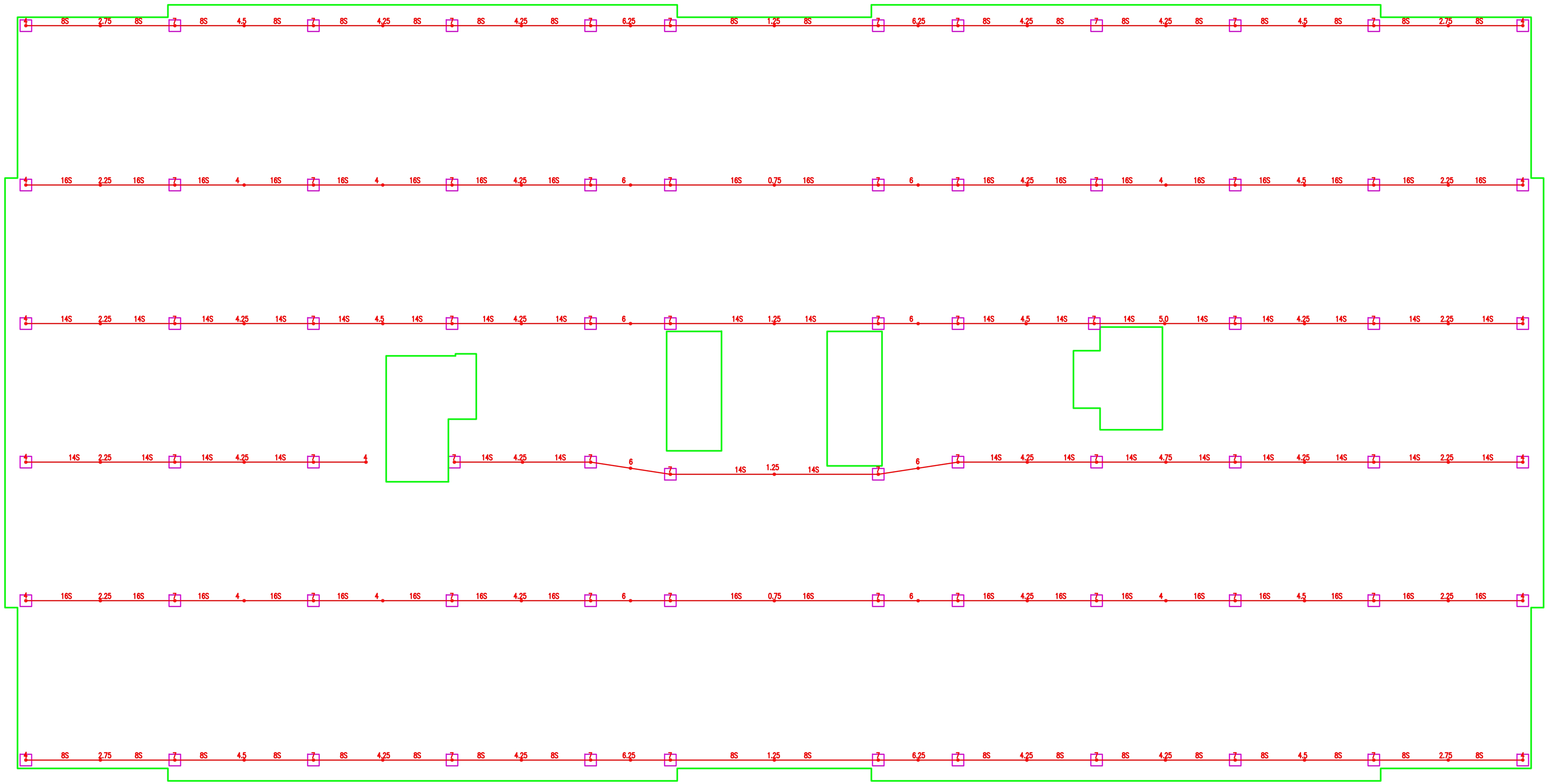


Bottom Bars: Latitude Direction



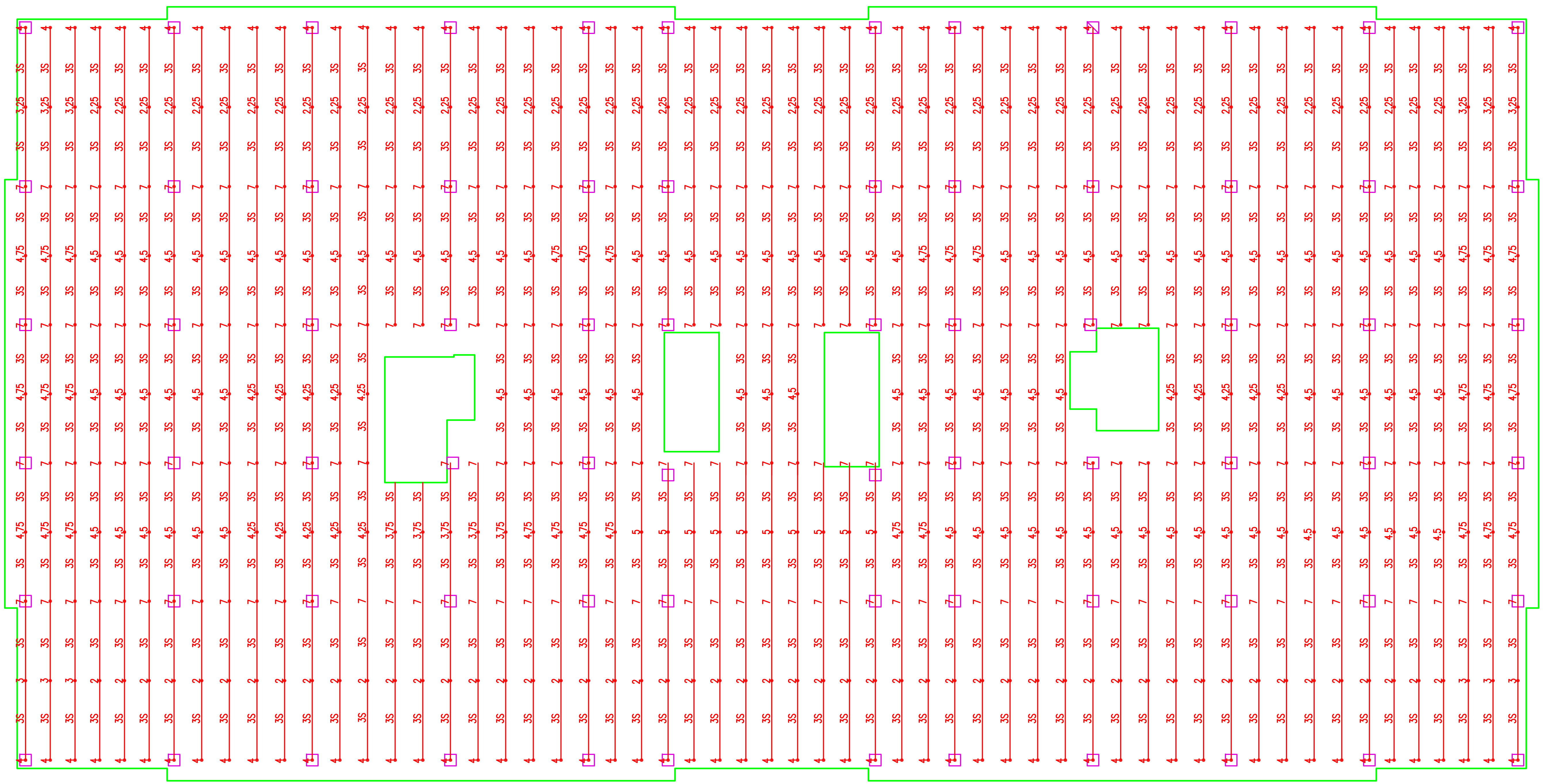
Latitude Tendon Layout: Banded Tendons

<u>Information Shown</u>
Number of Stands per Tendon Group
The Elevation of the Stands Within the Slab (Drape)



Longitude Tendon Layout: Distrubuted Tendons

Information Shown
Number of Stands per Tendon Group
The Elevation of the Stands Within the Slab (Drape)



Design Summary: Latitude Bottom Reinforcement Plan

Design Summary: User Lines; User Notes; User Dimensions; Latitude SSS Designs; SSS Design Bottom Bars; SSS Design Bar Descriptions; Latitude DS Designs; DS Design Bottom Bars;
Drawing Import: User Lines; User Notes; User Dimensions;
Element: Wall Elements Below; Wall Elements Above; Column Elements Below; Column Elements Above; Slab Elements; Slab Element Edges;
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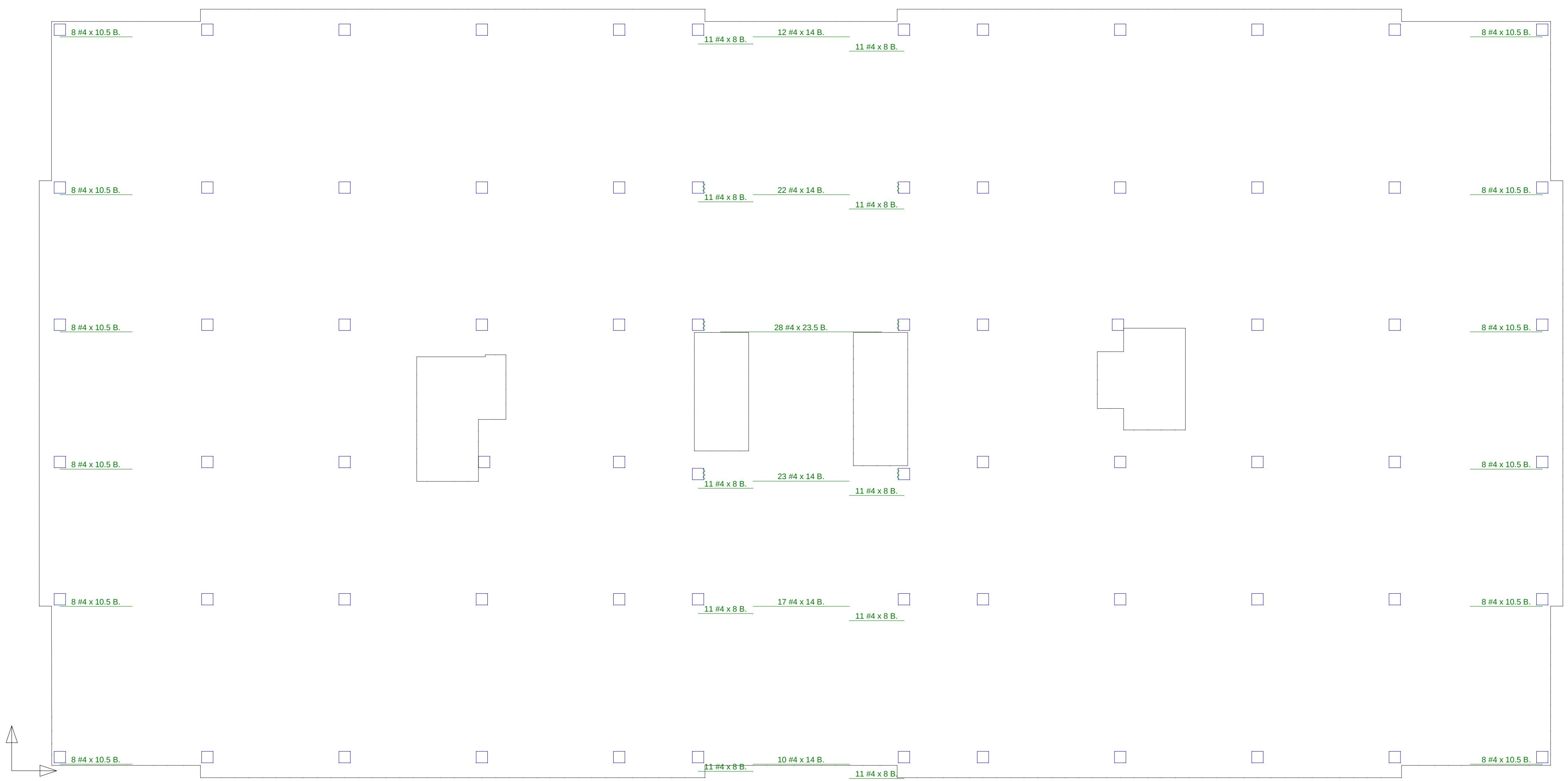

Design Summary: Latitude Top Reinforcement Plan

Design Summary: User Lines; User Notes; User Dimensions; Latitude SSS Designs; SSS Design Top Bars; SSS Design Bar Descriptions; Latitude DS Designs; DS Design Top Bars;
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Element: Wall Elements Below; Wall Elements Above; Column Elements Below; Column Elements Above; Slab Elements; Slab Element Edges;
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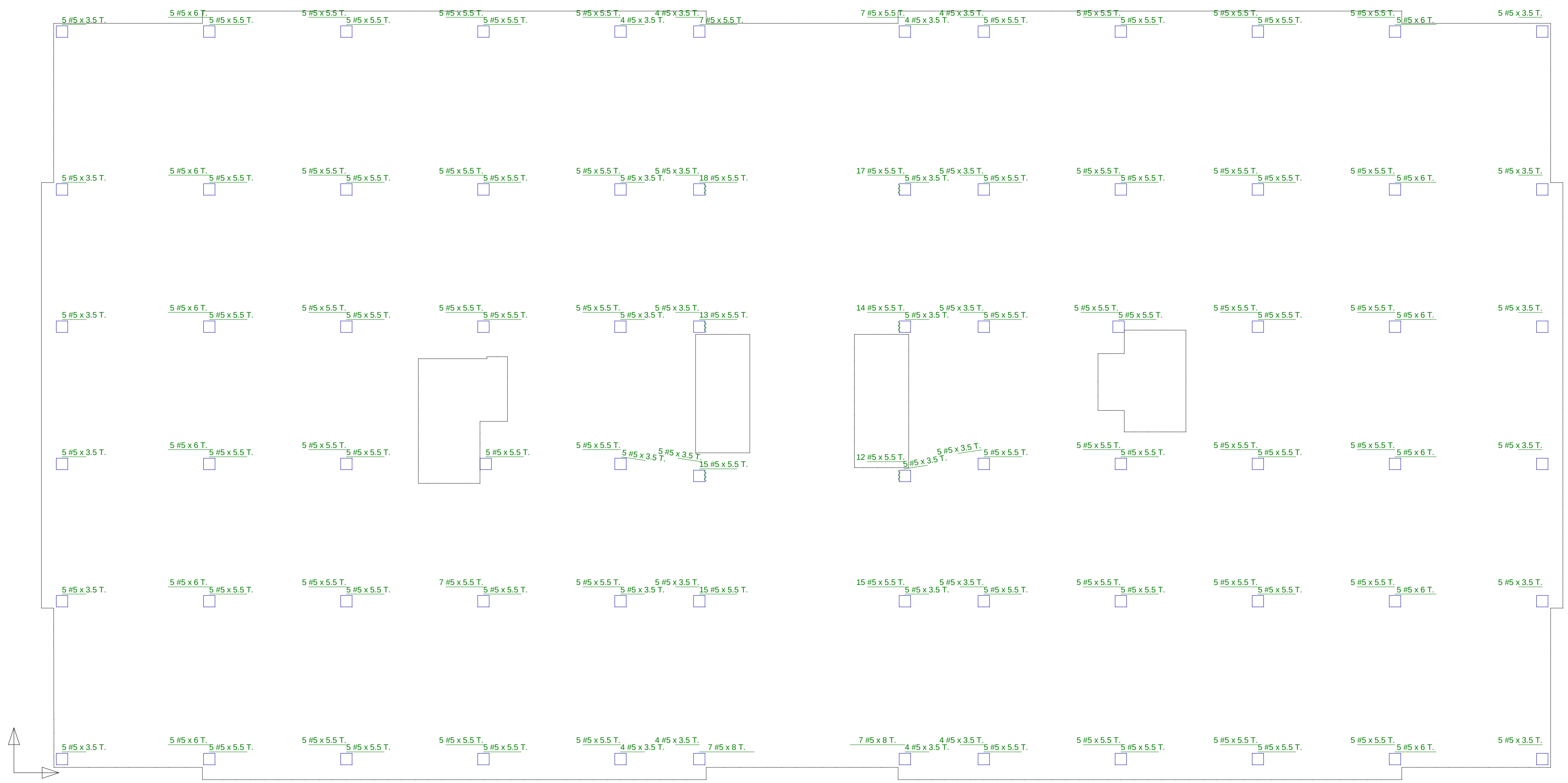

Design Summary: Longitude Bottom Reinforcement Plan

Design Summary: User Lines; User Notes; User Dimensions; Longitude SSS Designs; SSS Design Bottom Bars; SSS Design Bar Descriptions; Longitude DS Designs; DS Design Bottom Bars;
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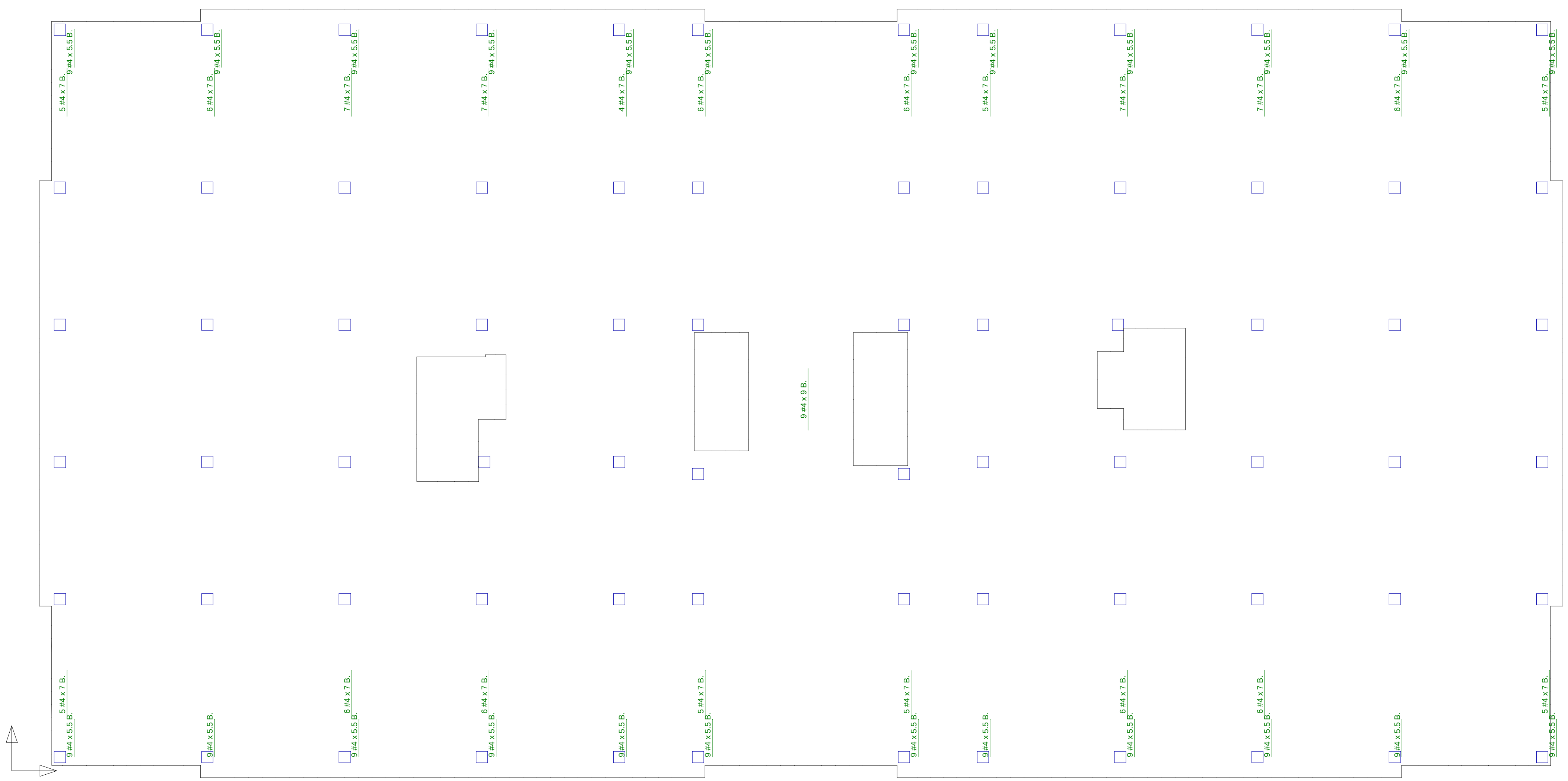

Design Summary: Longitude Top Reinforcement Plan

Design Summary: User Lines; User Notes; User Dimensions; Longitude SSS Designs; SSS Design Top Bars; SSS Design Bar Descriptions; Longitude DS Designs; DS Design Top Bars;
Drawing Import: User Lines; User Notes; User Dimensions;
Element: Wall Elements Below; Wall Elements Above; Column Elements Below; Column Elements Above; Slab Elements; Slab Element Edges;
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Design Strip: Latitude Design Spans Plan

Design Strip: User Notes; User Lines; User Dimensions; Latitude Span Boundaries; Latitude Strip Boundaries; Latitude SSs; Latitude SSSs; SSS Balance Percentages; Latitude DSs;
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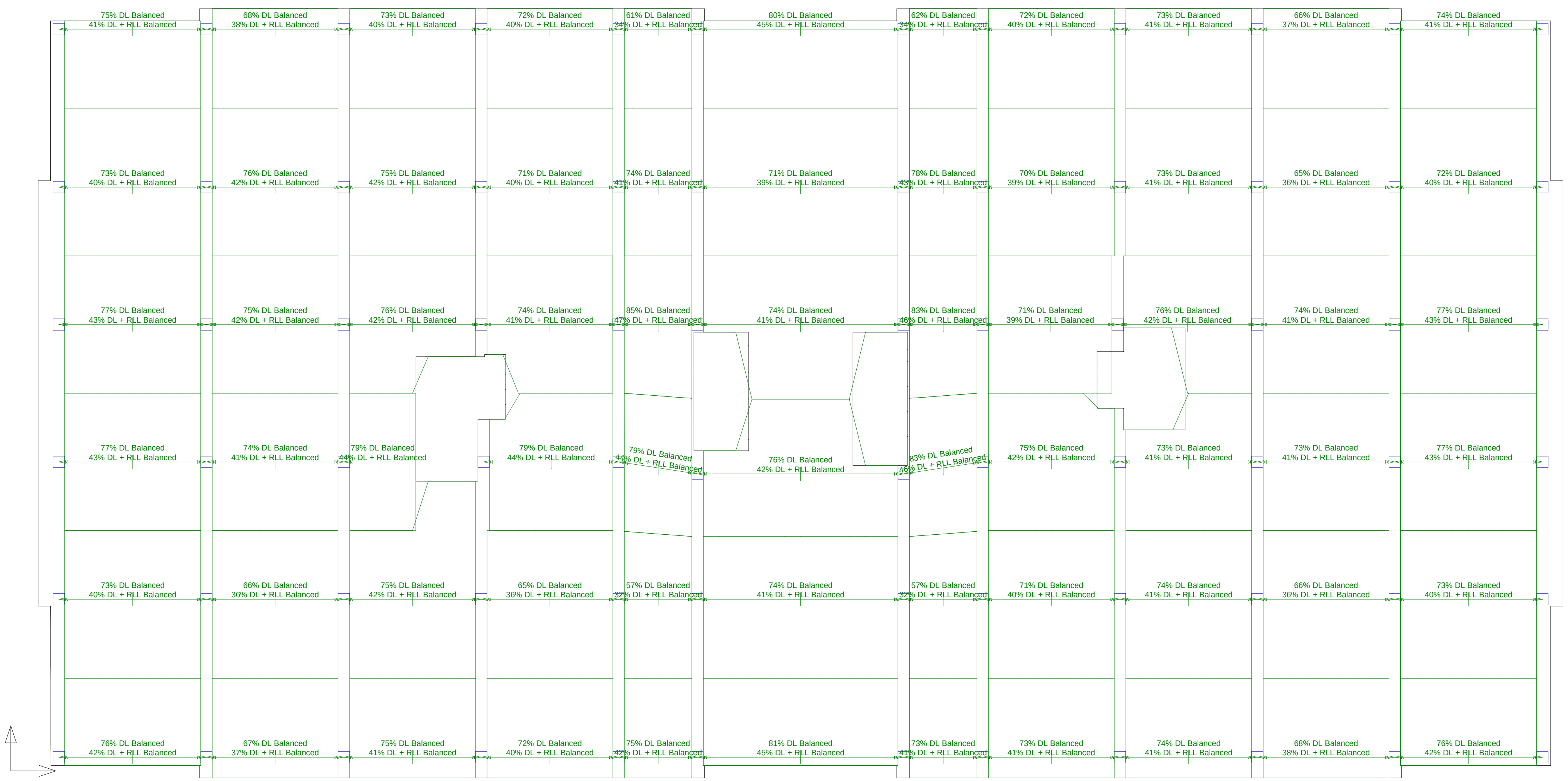

Design Strip: Longitude Design Spans Plan

Design Strip: User Notes; User Lines; User Dimensions; Longitude Span Boundaries; Longitude Strip Boundaries; Longitude SSs; Longitude SSSs; SSS Balance Percentages; Longitude DSs;
Drawing Import: User Notes; User Lines; User Dimensions;
Element: Wall Elements Above; Wall Elements Below; Column Elements Above; Column Elements Below; Slab Elements; Slab Element Edges;
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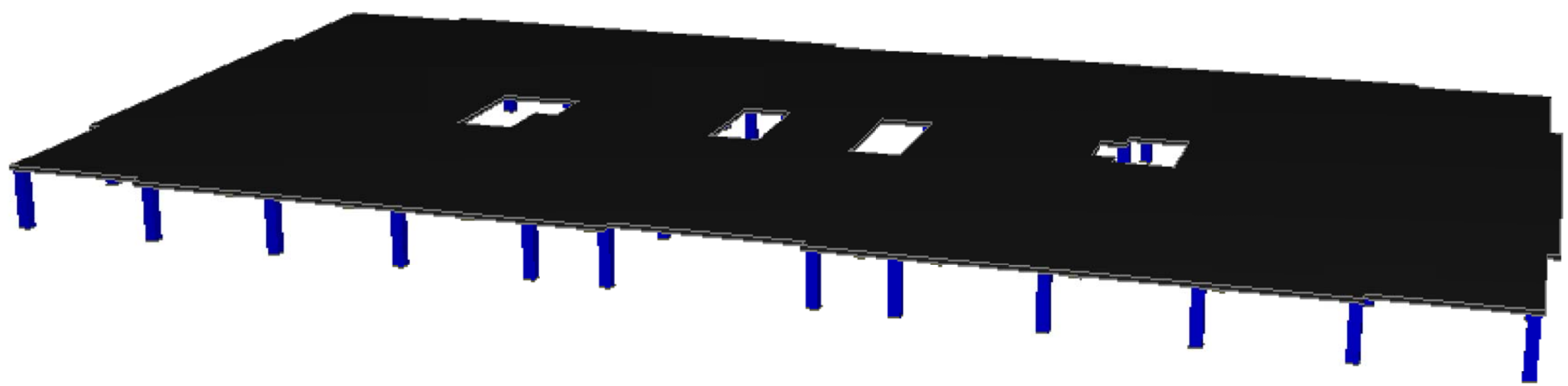
Element: Structure Summary Perspective

Wall Elements Below; Wall Elements Above; Column Elements Below; Column Elements Above; Slab Elements;
User Lines; User Notes; User Dimensions;



Service LC: D + (1.0 | 0.0) L: Deflection Plan

Service LC: D + (1.0 | 0.0) L: User Lines; User Notes; User Dimensions;
Drawing Import: User Lines; User Notes; User Dimensions;
Element: Wall Elements Below; Wall Elements Above; Column Elements Below; Column Elements Above; Slab Elements; Slab Element Edges;
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Vertical Deflection Plot

0.06 0.12 0.18 0.24 0.3 0.36 0.42 0.48 0.54

Min Value = -0.05342 inches @ (133.8,-1)   Max Value = 0.5294 inches @ (115,56.08)