Optimization of Building Systems and Processes

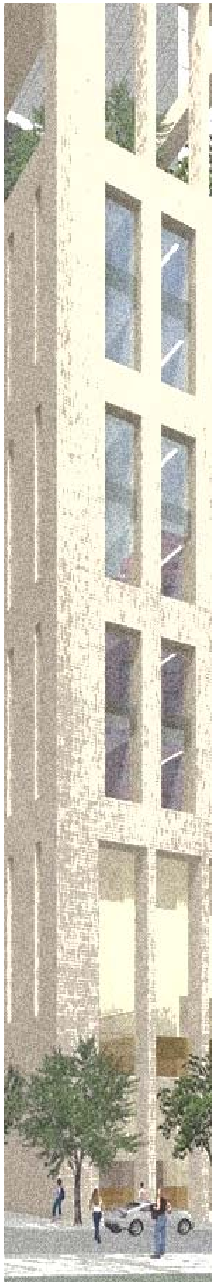
The Center for Science & Medicine

New York, NY

Ashley Bradford
Structural Option

AE Senior Thesis
April 15, 2008
Penn State University

Building Statistics

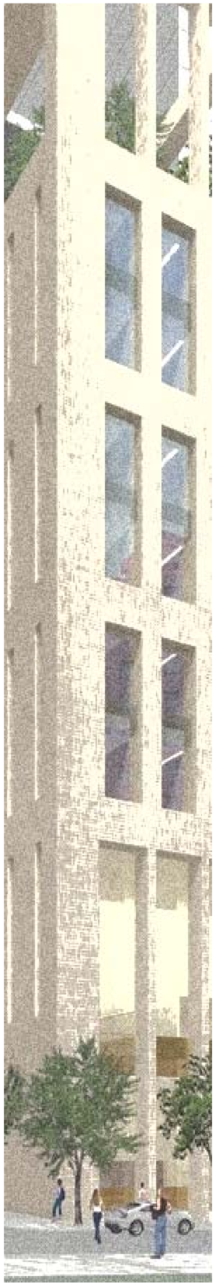


- Background Information
- Existing Conditions
- Proposal & Goals
- Lateral System Redesign
- Design Implications
- Cost Analysis
- Evaluation of Redesign
- BIM Case Study
- Lab Lighting Redesign
- Conclusions
- Questions

The Center for Science & Medicine

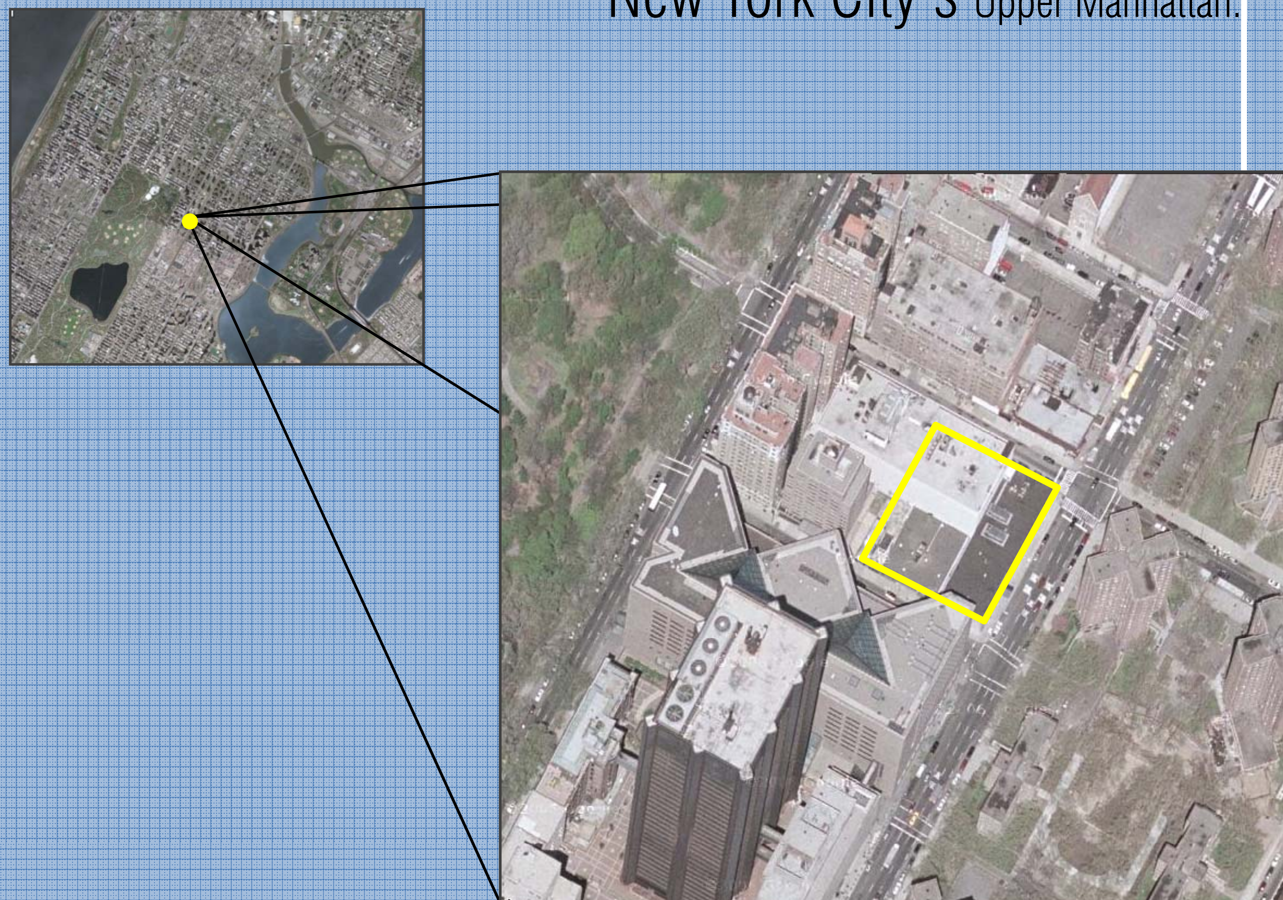
- Function: Laboratory for research & clinical trials
- Project Size: 443,291 sq. ft.
- Stories: 11 above grade, 4 below grade
- Total Cost: $235 million
- Construction: May 2008 – August 2011

Site Location



The Center for Science & Medicine will be located in

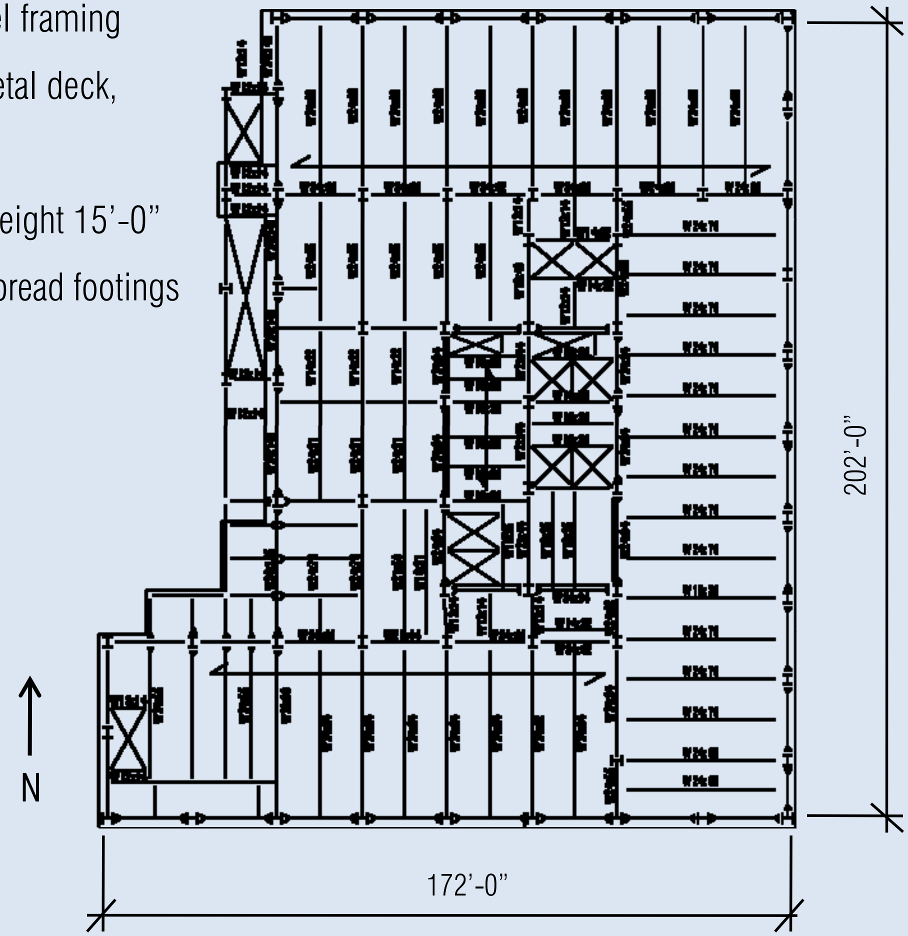
New York City's Upper Manhattan.



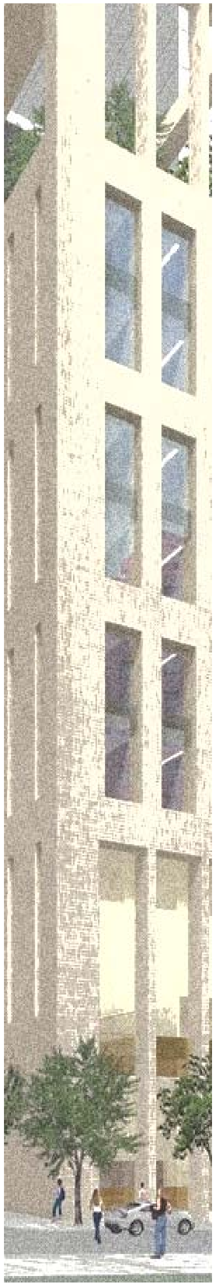
Existing Floor Framing & Foundations

Typical Framing Plan

- Structural steel framing
- Composite metal deck, NWC topping
- Typical floor height 15'-0"
- Foundation: spread footings



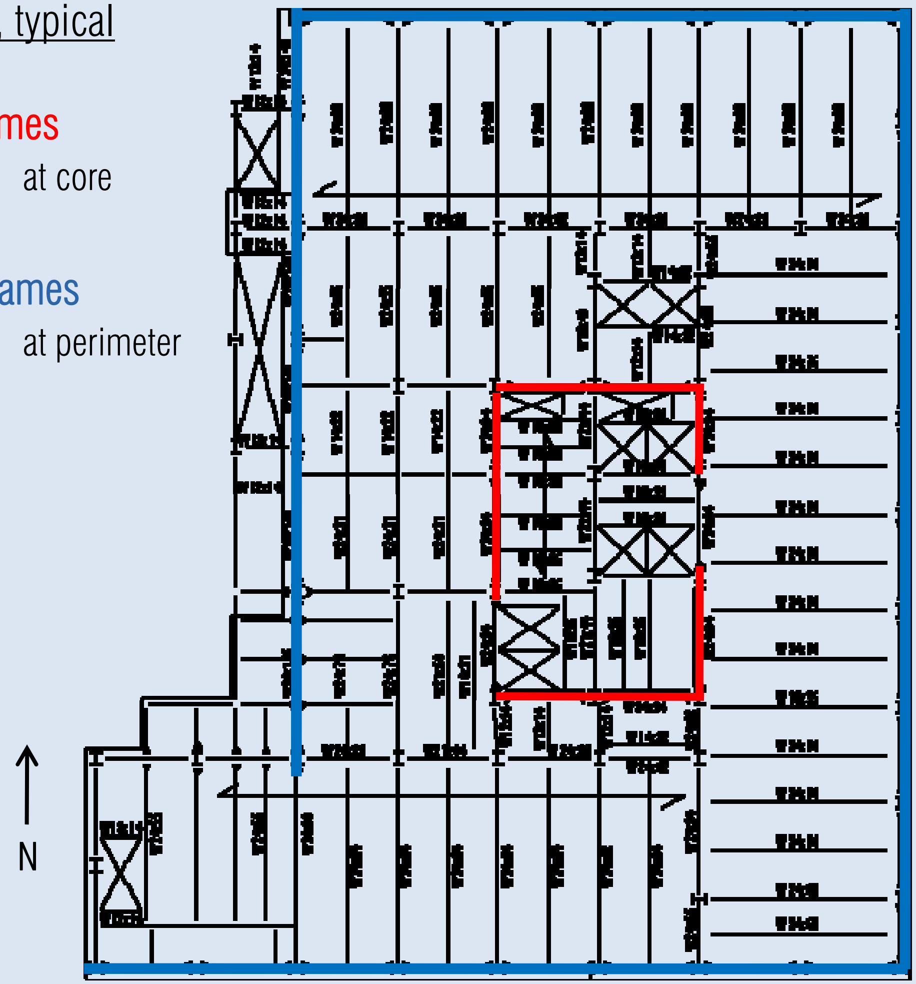
Existing Lateral System



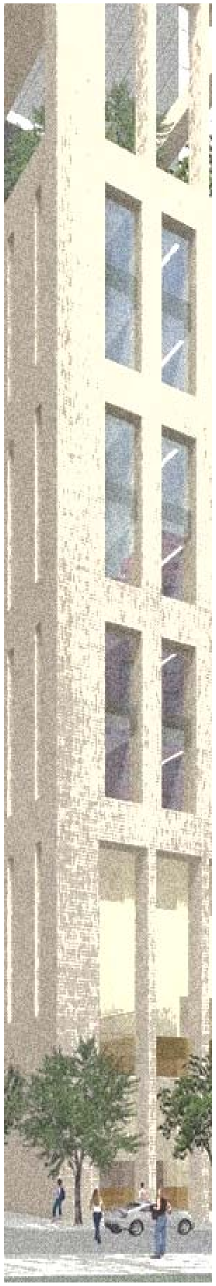
Levels 5-10, typical

Braced Frames at core

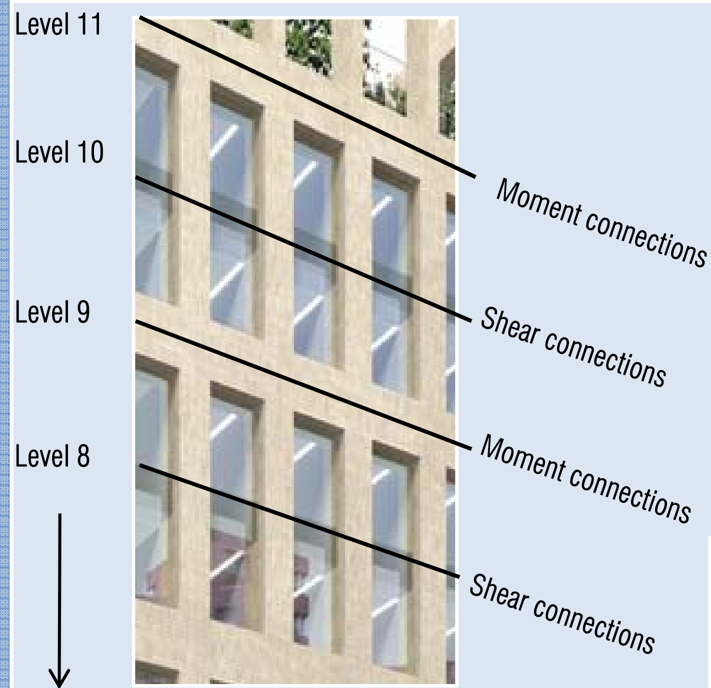
Moment Frames at perimeter



Existing Lateral System



Moment Frames

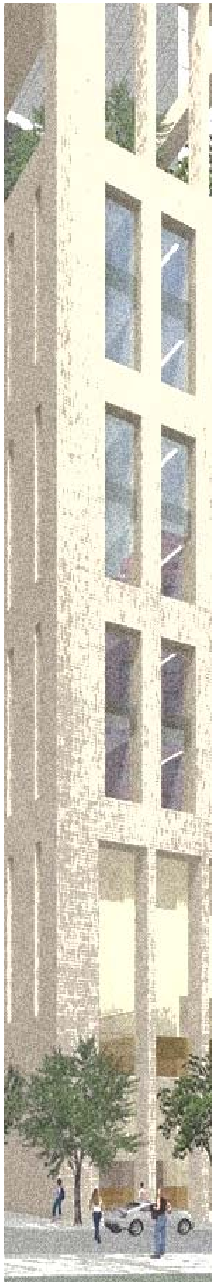


"Perforated" exterior cladding system:

façade appears to be punched by

alternating floor levels

Problem Statement



Existing Problem:

Moment frames are inefficient.

- Double-heighted configuration → frames are not as stiff.

  MF-A resists only 19% of E-W lateral load

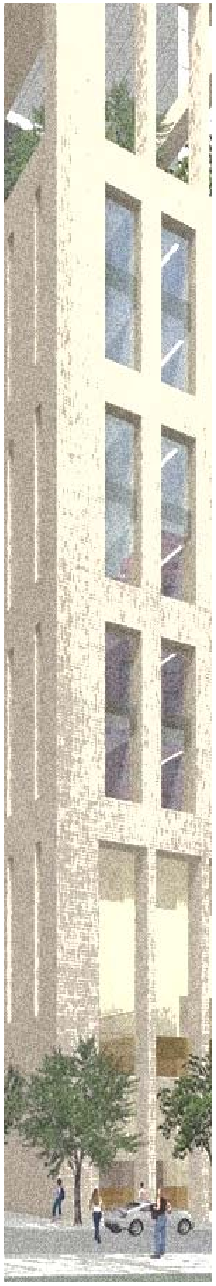
  MF-C resists only 14% of E-W lateral load

  MF-B resists only 3% of N-S lateral load

  MF-D resists only 5% of N-S lateral load

- At ≈ $1,000 per connection weld, these frames are very costly for the small amount of stiffness they provide for the structure.

Proposal and Goals



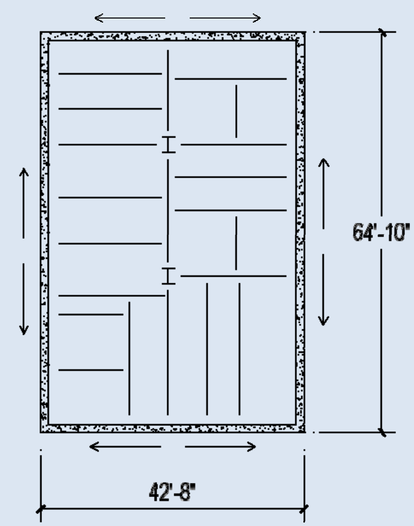
Overall Goal

Optimize building systems and processes.

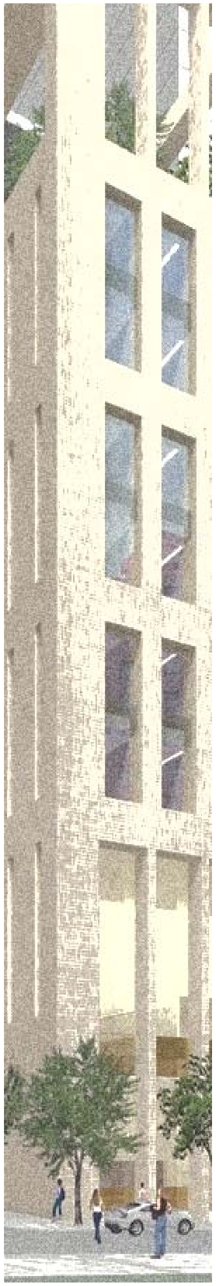
This will be accomplished by…

Proposal

- Redesign existing *lateral system* as a core-only system of concrete shear walls to eliminate moment frames.
- Address & optimize *construction issues* (automatic self-climbing formwork)
- Evaluate *3D modeling process* for efficiency and potential benefits
- Redesign typical *laboratory lighting* scheme for efficiency

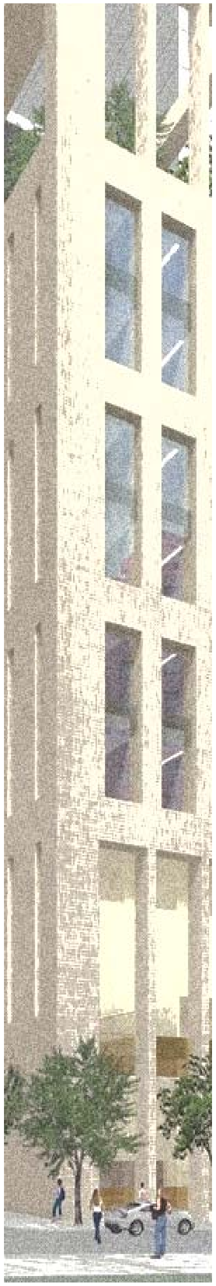


Depth Study



Lateral System Redesign

Lateral System Redesign



Applied Lateral Loads

- WIND = controlling lateral load case (over seismic)
- As per the NYC Building Code,

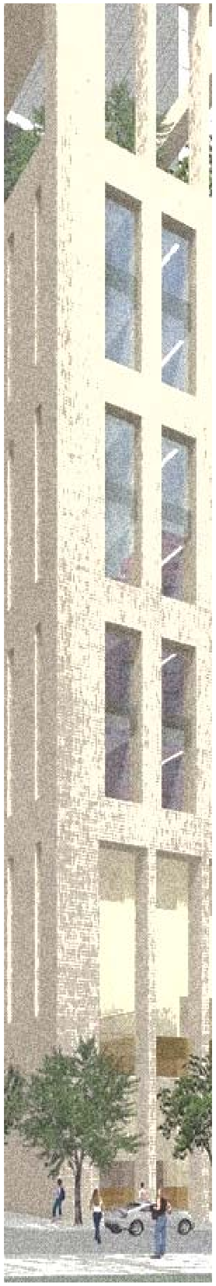
Height Zone (ft)	Design Wind Pressure on Vertical Surface (psf)
0-100	20
101-300	25
301-600	30
601-1000	35
Over 1000	40

- Total building height = 184'-0"

BASE SHEAR, E-W = 831 kips (1.4% total building weight)

BASE SHEAR, N-S = 707 kips (1.2% total building weight)

Shear Wall Design



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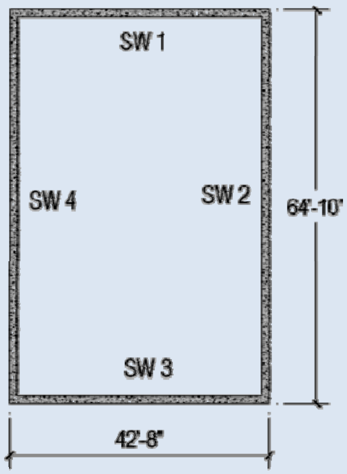
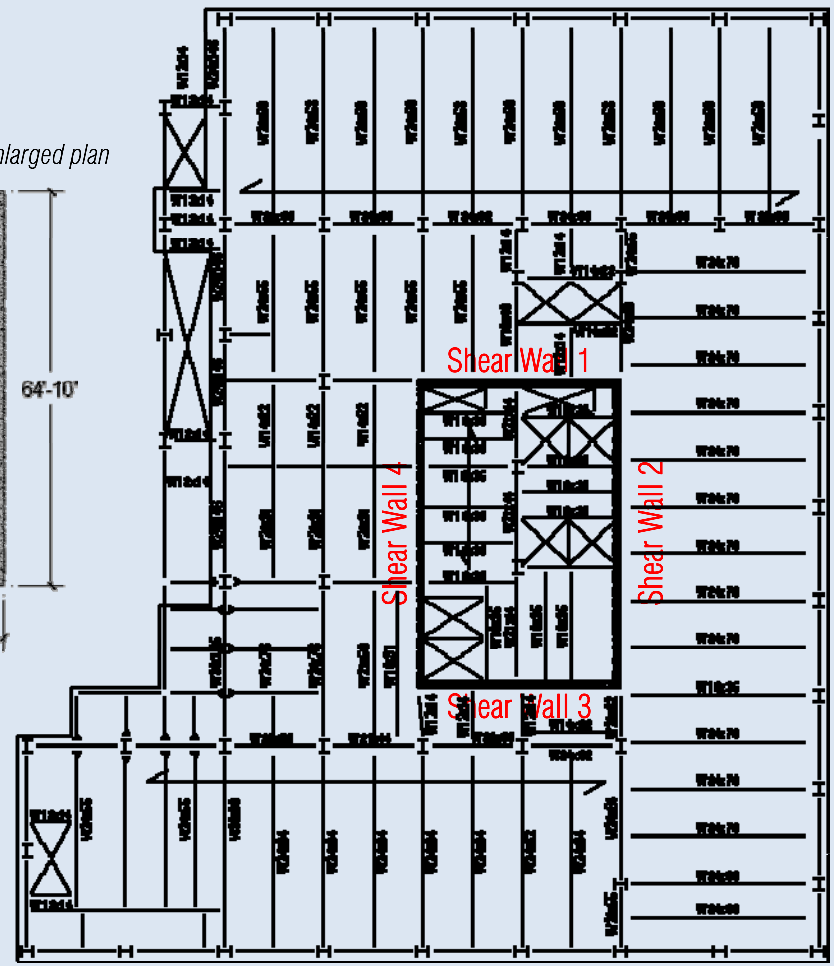
16" thick shear walls surround the core.

Shear Walls at Core, *enlarged plan*



Levels 5-10, typical



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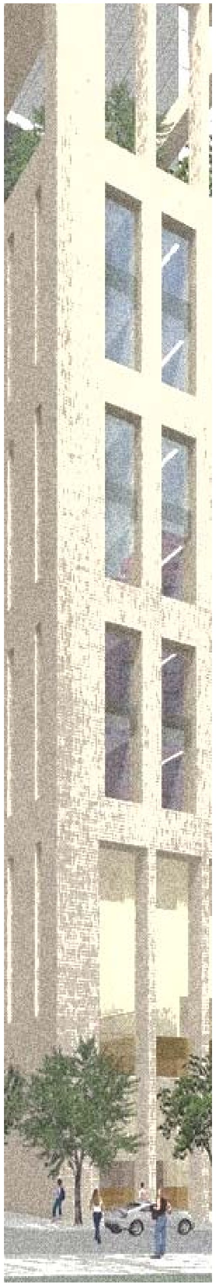

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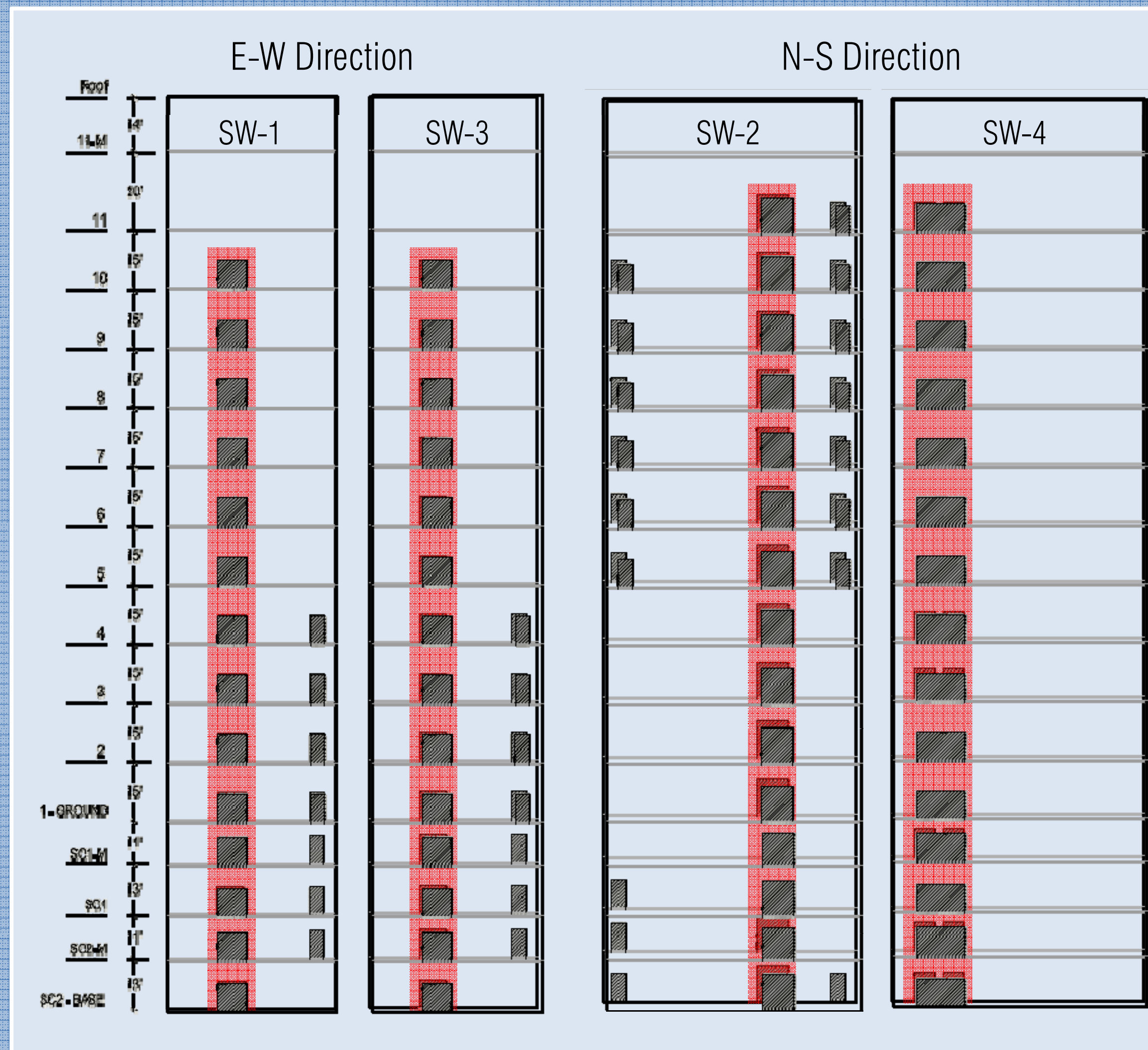
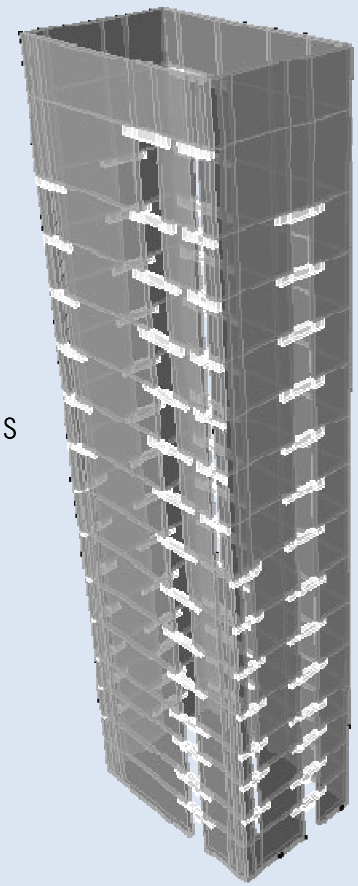
Configuration of Openings



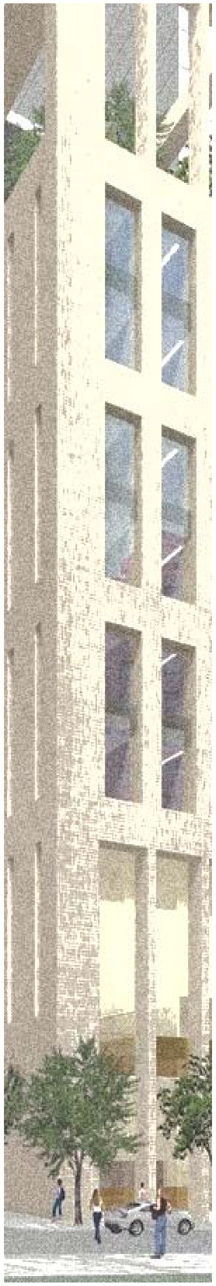
Shear Wall Design

ETabs Analysis: Equivalent Lateral Force Method

- Proposed lateral system modeled in ETabs for 2 purposes:
    1. To determine distribution of lateral load for strength design
    2. To check drift for serviceability limits
    - Rigid diaphragm
    - Cracked section properties
    - Rigid ends (coupling beams)
    - Infinitely stiff springs assigned to sub-grade levels
    - Input wind load cases: ASCE 7-05, Figure 6-9
    - Input load combinations: UBC 1997
        - 1.2D ± 0.8W
        - 1.2D ± 1.3W L
        - 0.9D ± 1.3W



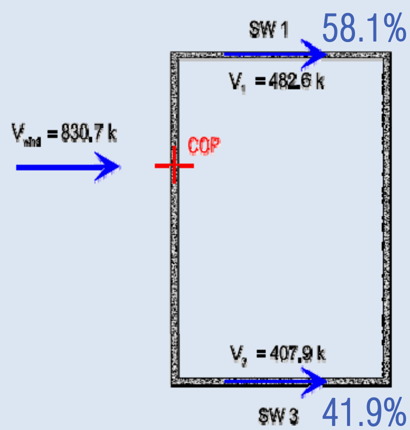
Shear Wall Design



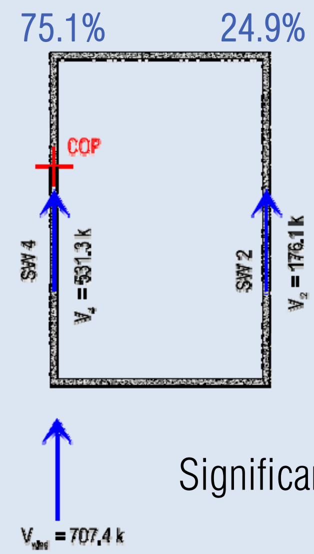
ETabs Analysis: Equivalent Lateral Force Method

Distribution of lateral load to each wall:

East-West

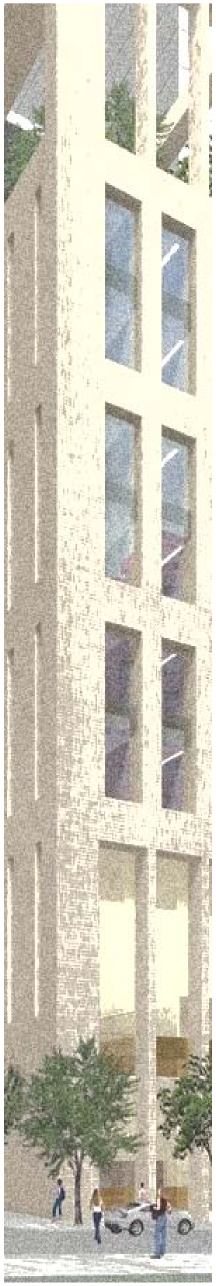


North-South



Significant torsion!

Shear Wall Design: Strength



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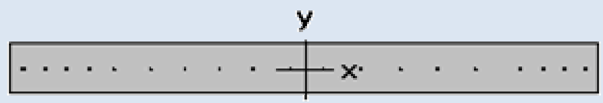
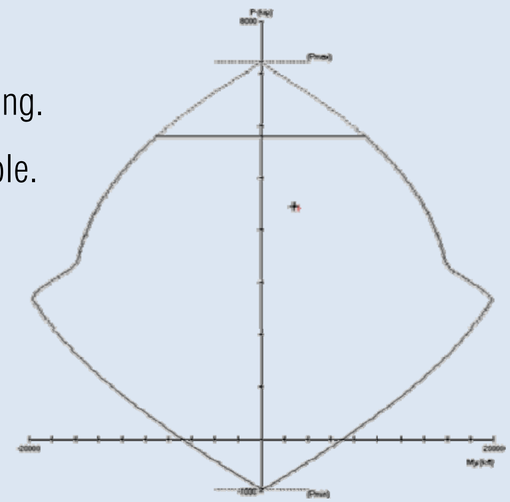
Design for Strength

Design Criteria & Methods
ACI 318-05, 21.7

- Maximum shear, axial forces & in-plane bending moments given by ETabs analysis.
- Required reinforcement calculated by hand.
- PCA Column to check combined axial/bending.
- Effective flanges considered, where applicable.

Example: Wall 1, Pier 2





Interaction Diagram for W1P1

Final Design

- Flexural reinforcement: (2 curtains) #5 @12," $\rho_{min} = \rho_{req'd} = 0.0025$
- Shear reinforcement: (2 curtains) #5 @12," $\rho_{min} = \rho_{req'd} = 0.0025$
- Boundary element reinforcement: #8 bars, typ. (transverse), $\rho_{req'd} = 0.01$

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Coupling Beam Design

Design Criteria & Method

ACI 318-05, 21.7

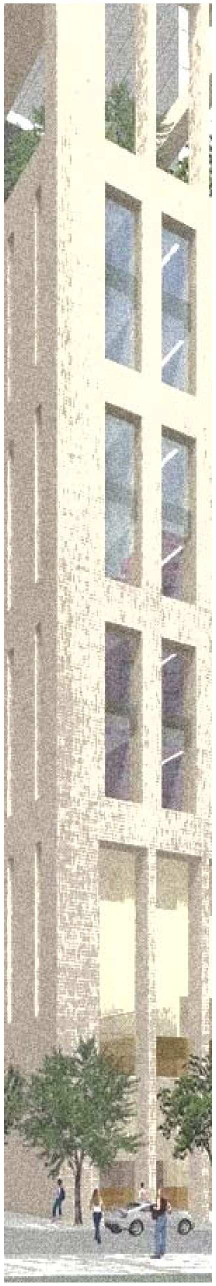
- Three different coupling beam sizes → Design determined by aspect ratio.

	4' span	8' span	13' span
f'c	4,000	4,000	4,000
Length (in)	48	96	156
Depth (in)	36	36	36
Width (in)	16	16	16
Acp (in^2)	768	1536	2496
Aspect Ratio, l/h	1.33	2.67	4.33
Reinforcement	Diagonals required.	Diagonals permitted.	Treat as flexural member of special moment frame.
Vu_{max}	30.2 k	49.4 k	41.5 k

Final Design

	4' span	8' span	13' span
Transverse Reinforcement	#3 hoops @ 5"	#3 hoops @ 5"	(2) #3 legs @ 8"
Longitudinal Reinforcement	(2) #3 bars @ 6"	(2) #3 bars @ 6"	(5) #8 bars, top & bot
Diagonal Reinforcement	2 diagonals of (4) #5 bars, $\alpha = 25^o$	2 diagonals of (4) #7 bars, $\alpha = 17^o$	N/A
Diagonal Confinement	#4 hoops @ 6"	#4 hoops @ 6"	N/A

Shear Wall Design: Strength



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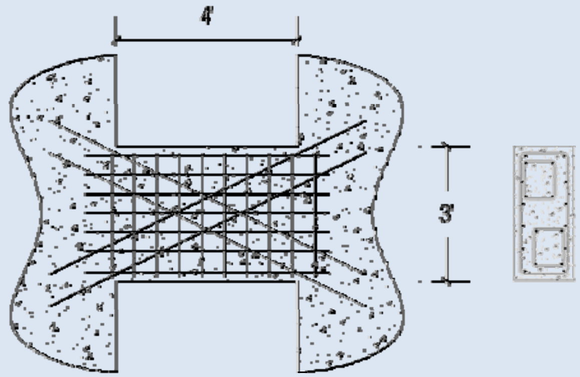
Design for Strength

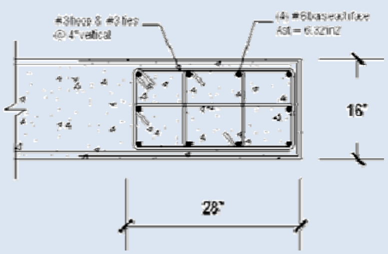
Final Design

Typical Details

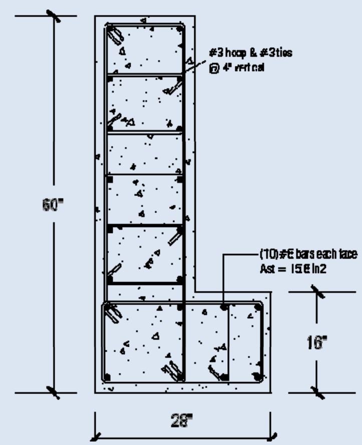
- 4' Span Coupling Beam



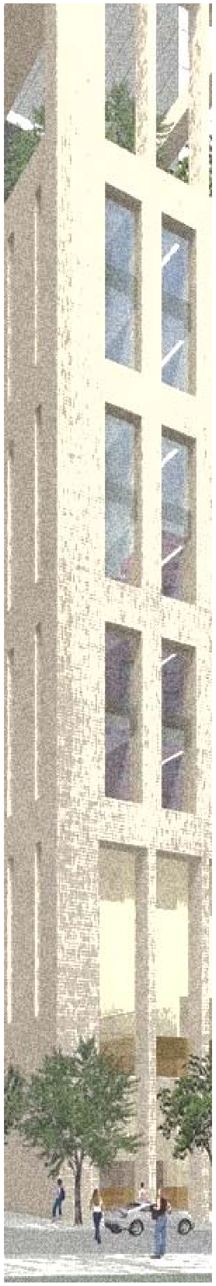
- Boundary Element at Opening (BE28)



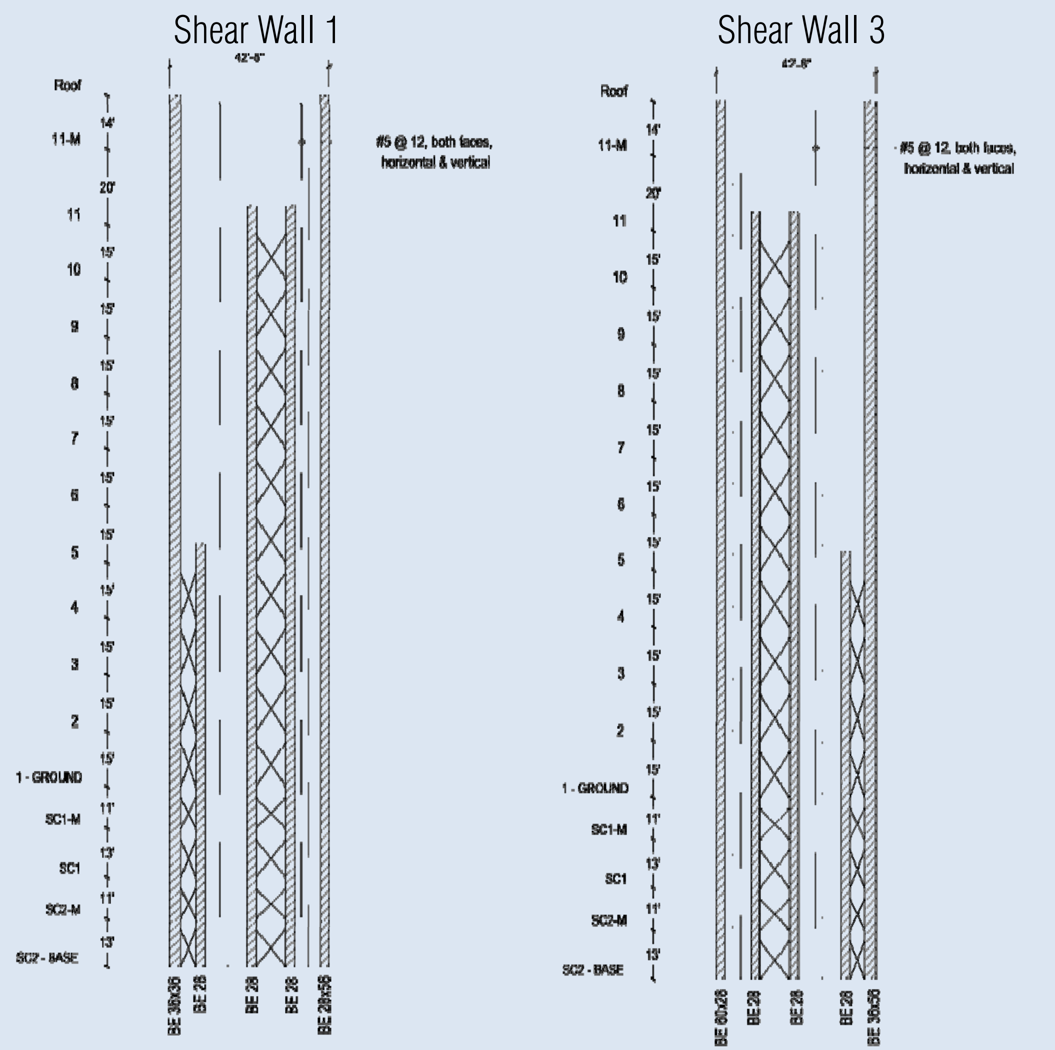
- Corner Boundary Element (BE28x60)



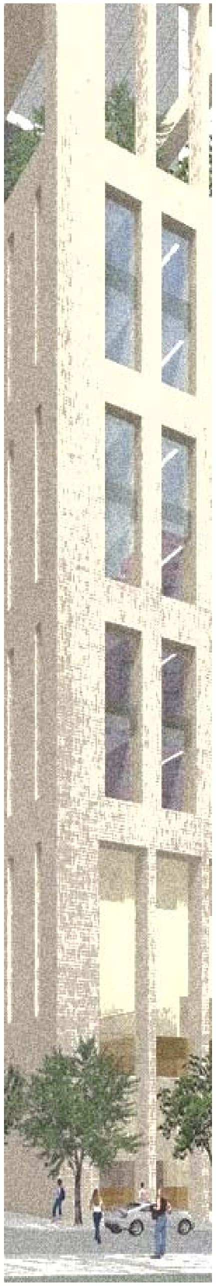
Shear Wall Design



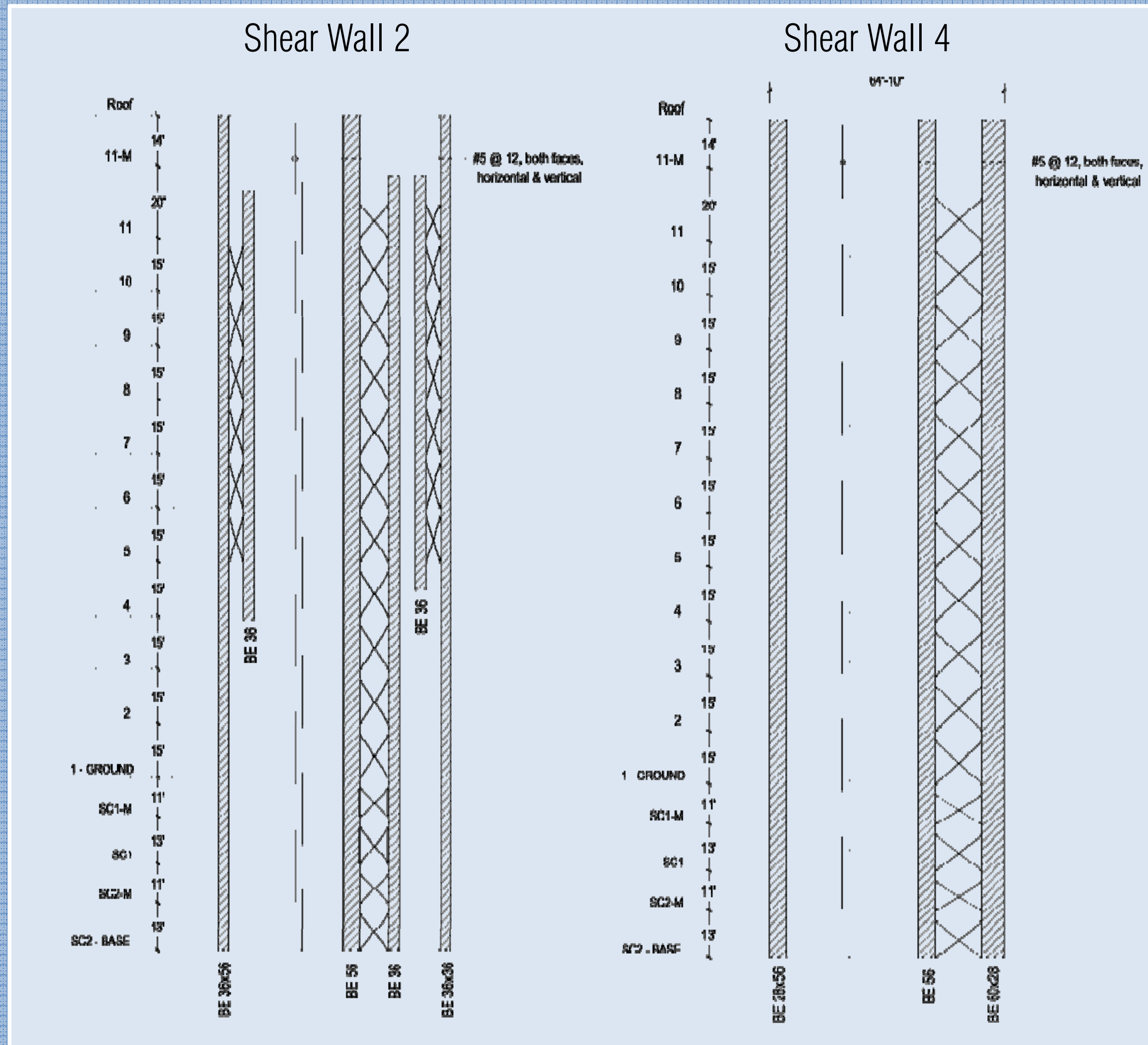
Final Shear Wall Design: E-W



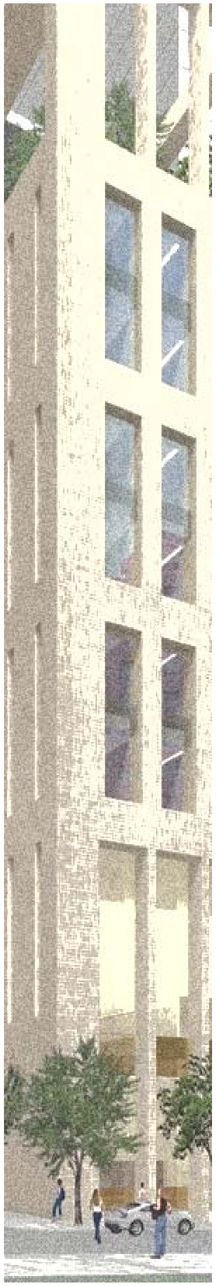
Shear Wall Design



Final Shear Wall Design: N-S



Shear Wall Design: Serviceability



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Check Serviceability

Building Drift

- WIND Drift Limits:

Overall Deflection (wind)		H/400
✓ E-W: 2.37”	<	5.52”
✓ N-S: 1.26”	<	5.52”

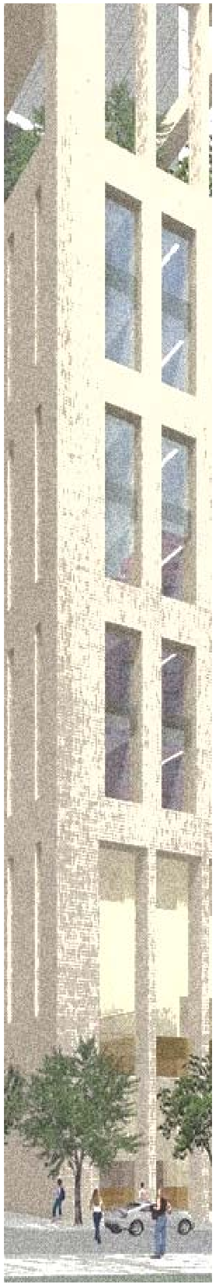
Interstory Drift		h/400
✓ E-W: 0.22”	<	0.45”
✓ N-S: 0.11”	<	0.45”

- SEISMIC Drift Limits:

Interstory Drift		$0.02h_{sx}$ x amp
✓ E-W: 0.13”	<	3.6”
✓ N-S: 0.08”	<	3.6”

✓ Proposed lateral system satisfies serviceability requirements.

Design Implications



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1. Gravity System

- W30 girders resized to W24s at perimeter.
- Vibration criteria still satisfied in laboratory areas
  - ✓ (2,000 μin/sec limit)

2. Foundation

- Existing spread footings would need to be redesigned as mat foundation.
- Consider overturning:

	Shear Wall 1	Shear Wall 2	Shear Wall 3	Shear Wall 4
Height	232 ft	232 ft	232 ft	232 ft
Length	42'-8"	64'-10"	42'-8"	64'-10"
Applied Wind Load	482.6 k	176.1 k	407.9 k	531.3 k
Overturning Moment	111,963 ft-k	40,855 ft-k	94,633 ft-k	123,192 ft-k
Resisting Dead Load	4533 k	8186 k	3716 k	8636 k
Resisting Moment	96,712 ft-k	264,779 ft-k	79,275 ft-k	184,241 ft-k
	$M_R < M_{OT}$	$M_R > M_{OT}$	$M_R < M_{OT}$	$M_R > M_{OT}$

Design Implications

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3. Construction Method

- Steel unions in New York City require that no trade work above them.
- Use this problematic circumstance to optimize the construction process.
- Solution:

PERI Automatic Climbing System (ACS) formwork

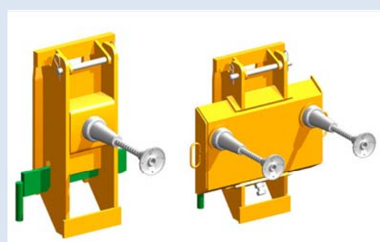
✓ Allows for steel-first construction

✓ Faster & more efficient than traditional flying forms

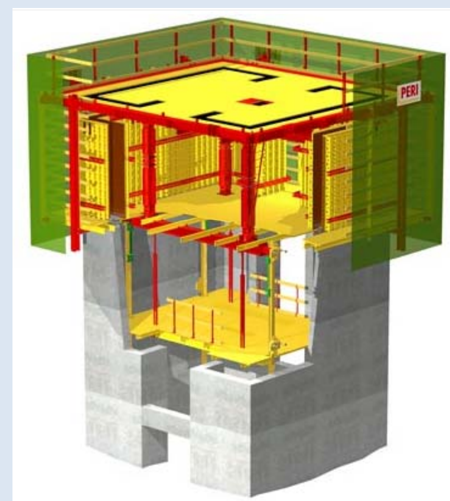
✓ Safer: no crane necessary

✓ Requires less physical labor

✓ Equipment cost ↑ ≈ Labor Cost ↓

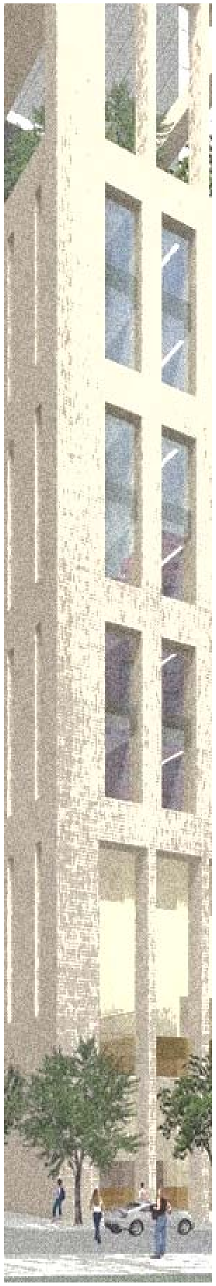


Courtesy of www.peri-usa.com



Courtesy of www.peri-usa.com

Cost Analysis



Approximate Cost Analysis

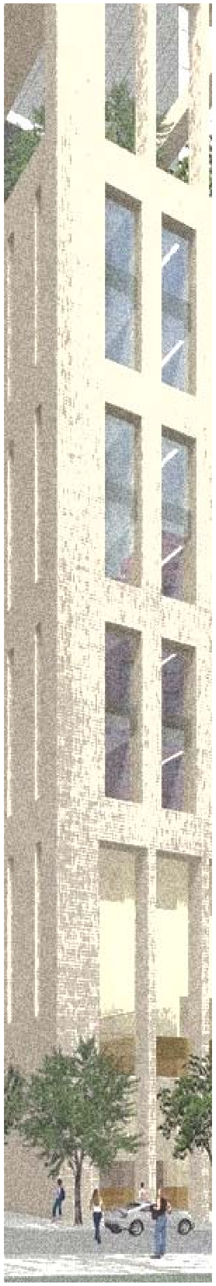
Savings Elimination of braced/moment frames	Expenses Addition of concrete shear walls
+ $1,486,400 (removed steel)	- $556,480 (materials & placement)
+ $1,346,000 (removed moment connections)	- $324,220 (formwork)
+ $2,832,400	(- $880,700)

Net savings = $1,951,700

≈ 1% total project cost

* Estimate does not include additional costs incurred by changes in foundation

Evaluation of Redesign



Original Goals

1.) Eliminate need for inefficient moment frames ✓

Core of shear walls resists 100% of lateral load

2.) Proposed system more efficient ✓

- STIFFNESS
- SCHEDULE

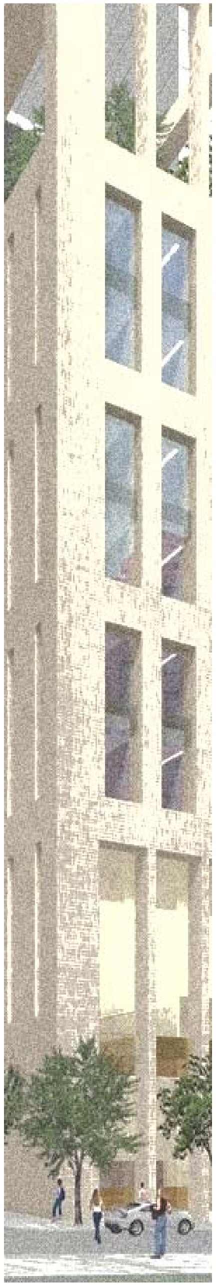
Shortened → no moment connections, quick automatic self-climbing formwork

3.) Proposed system more economical ✓

Overall savings almost $2 million.

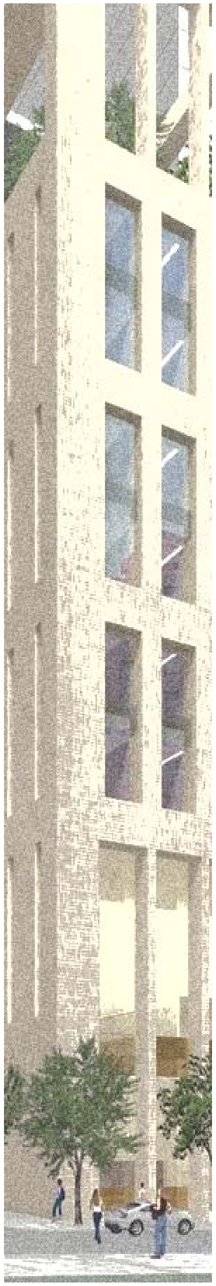
	Braced/Moment Frame Design (Original)	Shear Wall Design (Proposed)
E-W load	BF-1: 34% BF-3: 33% MF-A: 19% MF-C: 14%	SW-1: 58% SW-3: 42%
N-S load	BF-2: 35% BF-4: 57% MF-B: 3% MF-D: 5%	SW-2: 25% SW-4: 75%

Breadth Study 1



BIM Case Study

BIM Case Study



3D Modeling

Designer Skidmore, Owings & Merrill used Autodesk's Revit throughout the design process.

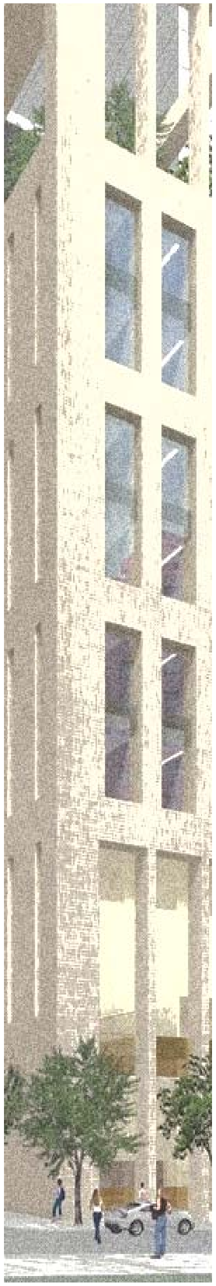
- Architectural
- Structural
- MEP

Does building information modeling truly optimize the design process?

Interviews conducted with:

- Project Architect
- Project Structural Engineer
- Digital Design Specialist
- Digital Design Coordinator / Structural Drafter

BIM Case Study



3D Modeling

How it Works: a 5-day cycle in the office

Each discipline has its own working 3D model

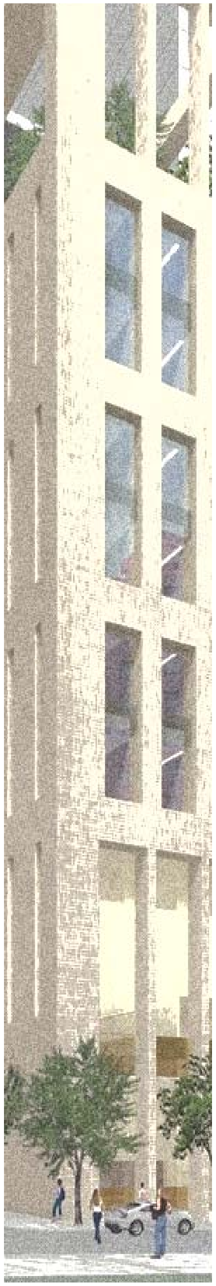
Days 1 & 2 → Architects post "static" model for all engineers to access

Day 3 → Engineering disciplines submit models, all are linked

Day 4 → Coordination meeting held between all disciplines

Day 5 → Necessary changes made to all models, as determined in meeting

BIM Case Study



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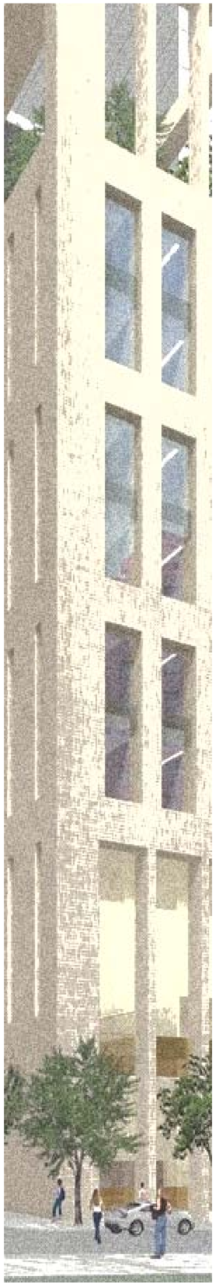
Evaluation of 3D Modeling Implementation

PROS	CONS
✓ Project quality improvement	X Training required
✓ More coordination early-on	X Learning curve
✓ Less conflicts during CD phase & construction phase	X "Heavy" models
✓ Same amount of total design hours	

Does building information modeling truly <u>optimize</u> the design process?

Yes.

Breadth Study 2



Laboratory Lighting Redesign

Laboratory Lighting Redesign

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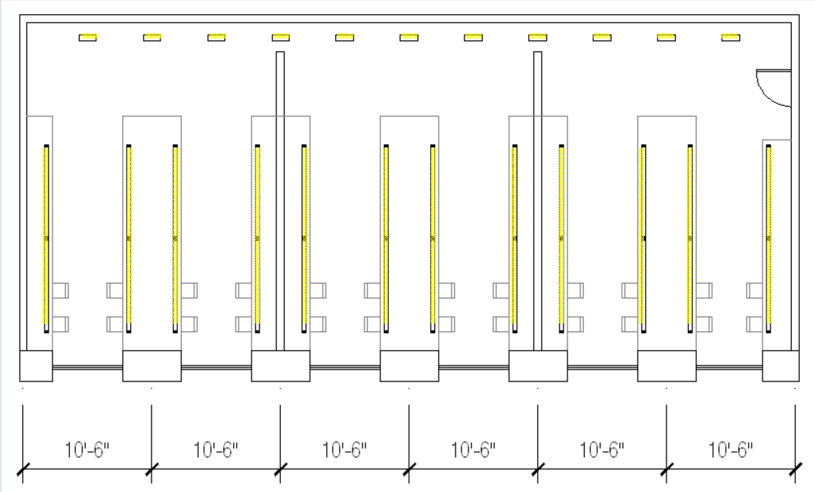
Typical Laboratory Existing Conditions

Existing Lighting Plan

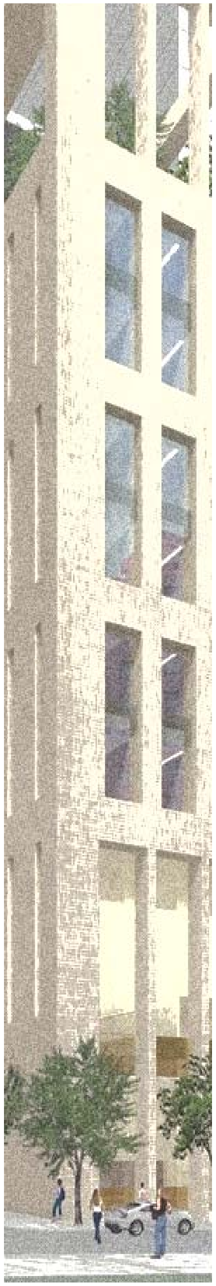


Current Fixtures:

- Surface ceiling mounted fluorescent wraparounds with (2) 32W T8 lamps (61.5% efficiency)
- Recessed fluorescents with (2) 40W twin tube T5 lamps

	Calculated Value		Limit	Reference
Power Density	1.76 W/ft²	> TOO HIGH	1.4 W/ft² maximum	ASHRAE Standard 91.1
Avg. Ambient Illuminance	59.2 FC	> TOO HIGH	40 - 50 FC target	Criteria provided by designer.
Avg. Bench Top Illuminance (37")	97.4 FC	> TOO HIGH	70 - 80 FC target	Criteria provided by designer.

Laboratory Lighting Redesign



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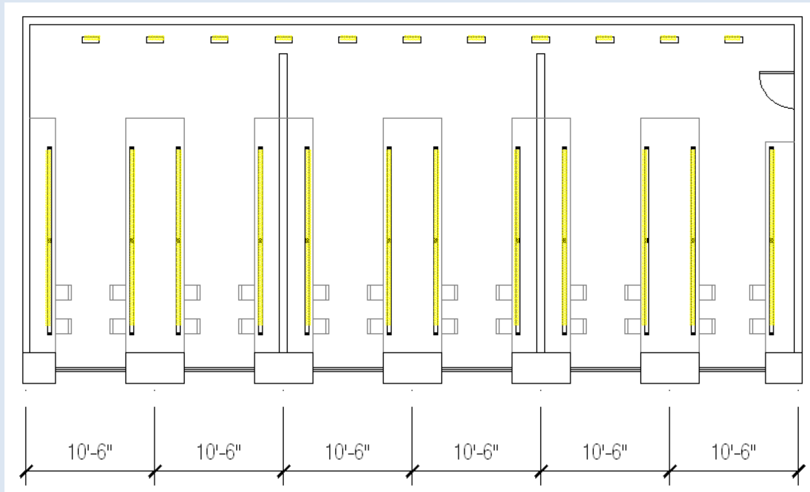
Typical Laboratory Existing Conditions

Proposed Lighting Plan

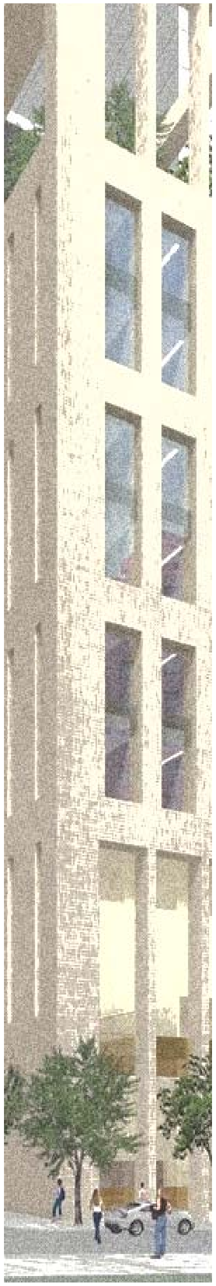


Proposed Fixtures:

- Corelite Class R2 Shallow Recessed Fluorescent with (1) 24W 48" T5 lamp (85% efficiency)
- Recessed fluorescents with (2) 40W twin tube T5 lamps

	Calculated Value		Limit	Reference
Power Density	1.02 W/ft² ✓	< Acceptable	1.4 W/ft² maximum	ASHRAE Standard 91.1
Avg. Ambient Illuminance	51.1 FC ✓	≈ Acceptable	40 - 50 FC target	Criteria provided by designer.
Avg. Bench Top Illuminance (37")	77.3 FC ✓	= Acceptable	70 - 80 FC target	Criteria provided by designer.

Final Conclusions



Primary Goal:

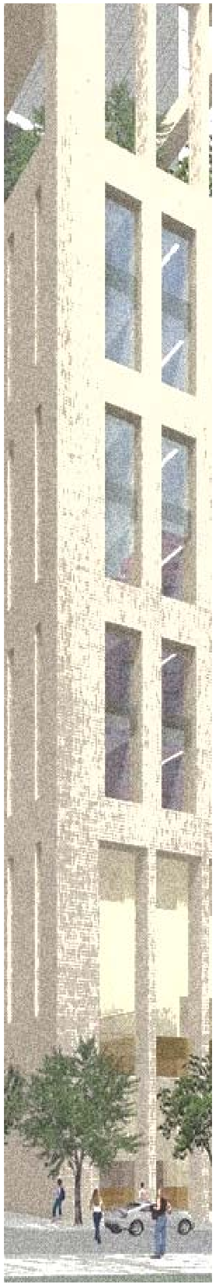
<u>Optimize</u> building systems and processes:

Was this accomplished?

- Building Systems:
  - Core-only lateral system is more efficient & economical ✓
  - Lab lighting redesign now meets ASHRAE standard and defined design criteria ✓
- Building Processes:
  - PERI ACS formwork is faster & safer ✓
  - 3D modeling in Revit highly beneficial ✓

Overall success.

Optimization of Building Systems and Processes



Questions?

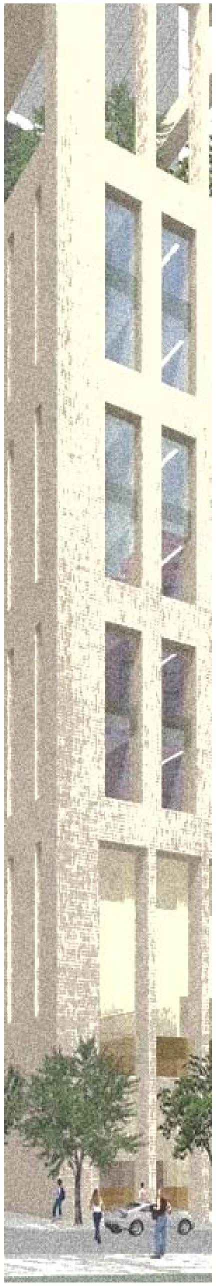
Acknowledgements

Skidmore, Owings & Merrill, LLP – CUH2A, Inc. – KPFF Consulting Engineers – PERI Formwork, Inc.

Dr. Andres LePage – M. Kevin Parfitt – Robert Holland – Dr. John Messner – Dr. Richard Mictrick

Bryan Hart – Landon Roberts – Allen Walker – Julie Davis – Antonio Verne – My Roommates – My Family

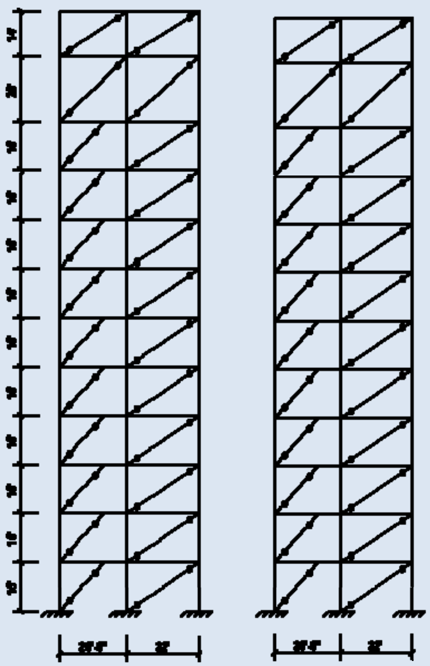
Existing Lateral System



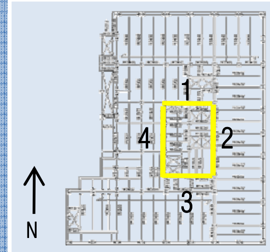
Braced Frames

East-West

BF-1 BF-3

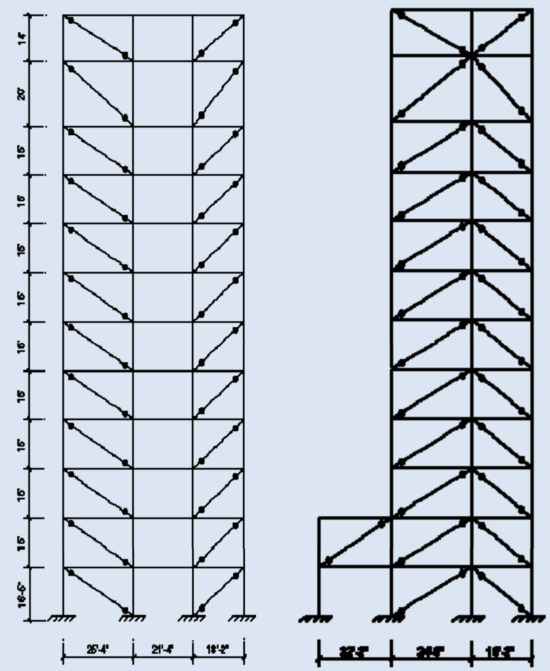


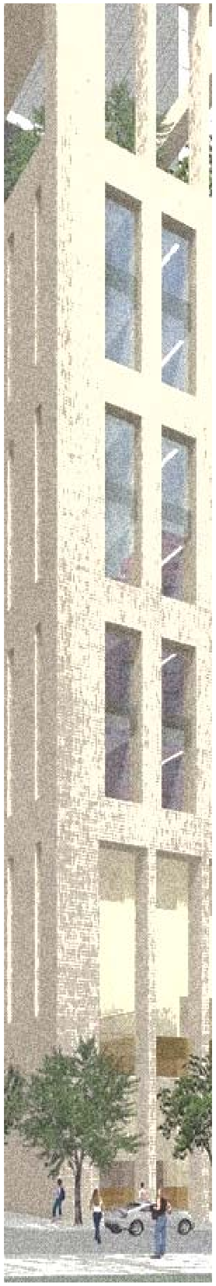
- Frames braced concentrically by (2) heavy double tee sections
- WT6x39.5 - WT6x68



North-South

BF-2 BF-4



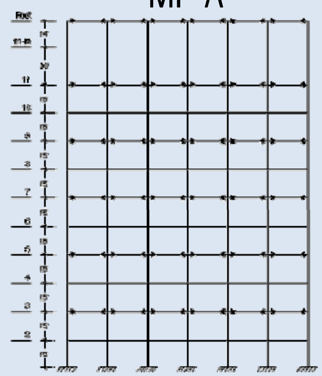


Existing Lateral System

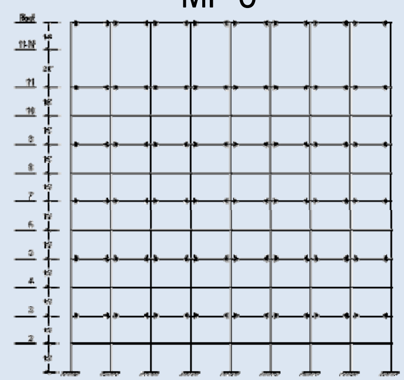
Moment Frames

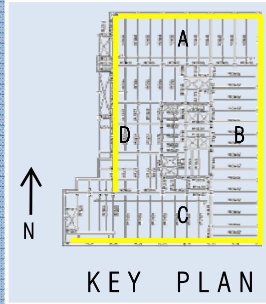
East-West

MF-A



MF-C

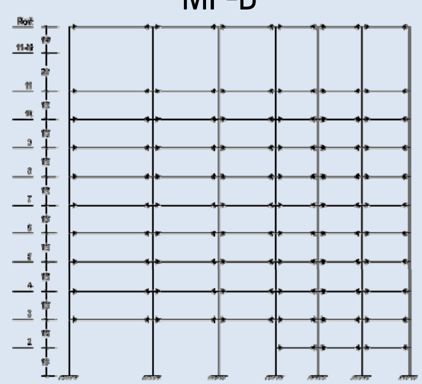




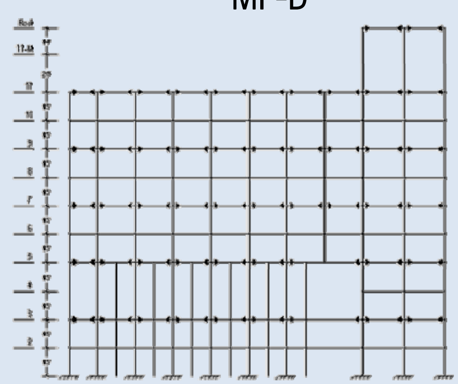
- W14 and W24 shapes
- Moment connections occur on every other level

North-South

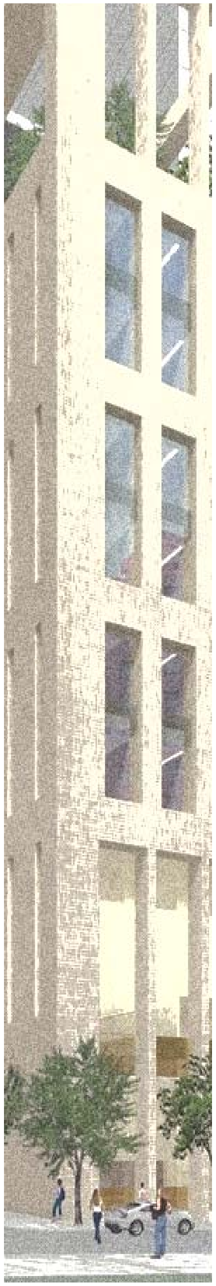
MF-B



MF-D



Lateral System Redesign

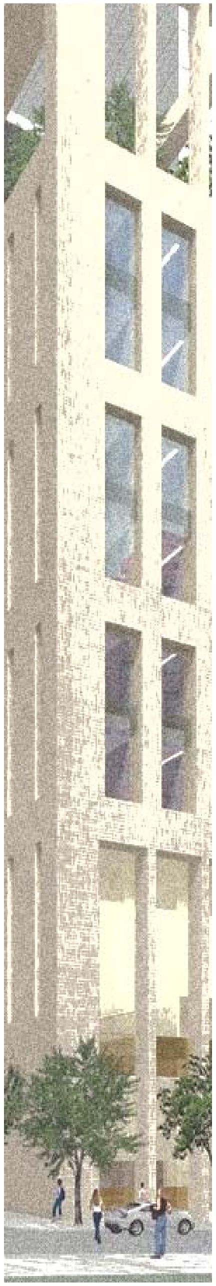


Applied Lateral Loads

Windward Pressures:

Story	Height Above Grade (ft)	Windward Pressure (psf)	Windward X (kips)	Windward Y (kips)
Roof	184	25	35.4	30.1
11-M	170	25	85.9	73.1
11	150	25	88.4	75.3
10	135	25	75.8	64.5
9	120	25	75.8	64.5
8	105	25	75.8	64.5
7	90	20	60.6	51.6
6	75	20	60.6	51.6
5	60	20	60.6	51.6
4	45	20	60.6	51.6
3	30	20	60.6	51.6
2	15	20	60.6	51.6
1	0	20	30.3	25.8
		Base Shear: ∑ =	830.7	707.4
		% of bldg weight =	1.40	1.19
		Factored Base Shear (x 1.3): ∑ =	1079.9	919.6

Lateral System Redesign



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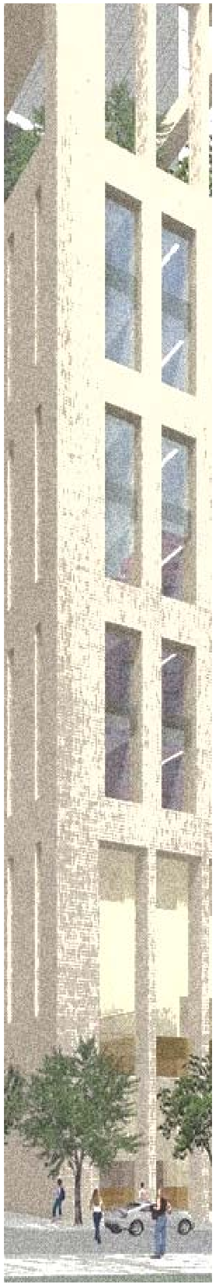
Applied Lateral Loads

Seismic Loads, per NYC Building Code

Level	Elevation	w_i (given)	SW weight	w_i (kips)	$w_i h_i$ (k-ft)	Fx (kips)
Roof	184	4073	0	4073	749,432	157.0
Level 11-M	170	512	665	1177	200,090	41.9
Level 11	150	6850	950	7800	1,170,000	245.2
Level 10	135	3423	713	4136	558,293	117.0
Level 9	120	4184	713	4897	587,580	123.1
Level 8	105	3453	713	4166	437,378	91.6
Level 7	90	4211	713	4924	443,115	92.9
Level 6	75	3460	713	4173	312,938	65.6
Level 5	60	4175	713	4888	293,250	61.4
Level 4	45	3176	713	3889	174,983	36.7
Level 3	30	4220	713	4933	147,975	31.0
Level 2	15	4208	713	4921	73,808	15.5
Level 1	0	5835	713	6548	0	0.0
			Seismic Base Shear (unfactored):		$\Sigma =$	1078.9

Seismic Design Values, NYC Building Code (references UBC 1997)		
Occupancy	I	
Importance Factor	I = 1.25	(Essential & Hazardous Facility)
Period, T	T = 1.89 sec	(from E-Tabs analysis)
S	0.67	(Rock, per Langan Report)
Z	0.15	(Zone 2A, per Langan Report)
R_w	5	(Shear Walls)
Diaphragm	Rigid	



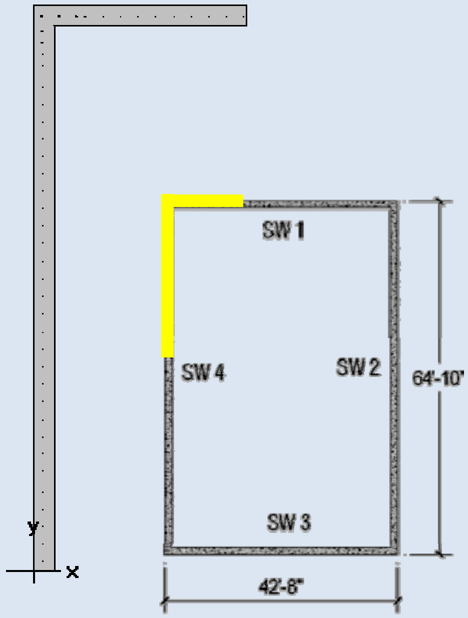
Shear Wall Design: Strength

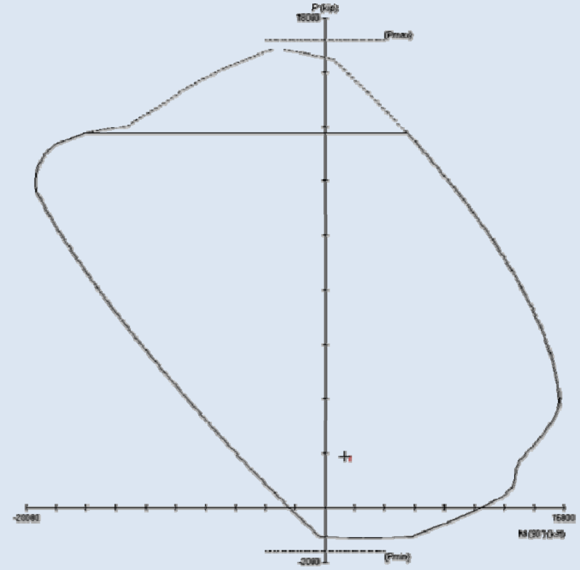
Design for Flexure and Shear

Flexural Strength: ACI 318-05, 21.7

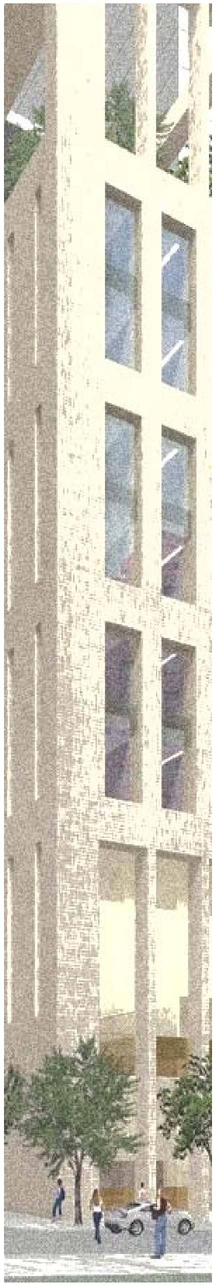
- Maximum axial forces and in-plane bending moments given by ETabs.
- PCA Column used to check combined axial/bending.
- Effective flanges considered, where applicable.

Example: Wall 1, Pier 1 (base)





Lateral System Redesign



Design for Strength

Shear Strength

Nominal shear strength for structural walls shall not exceed:

$$V_n = A_{cv}\left(\alpha_c \sqrt{f'_c} + \rho_n f_y\right)$$

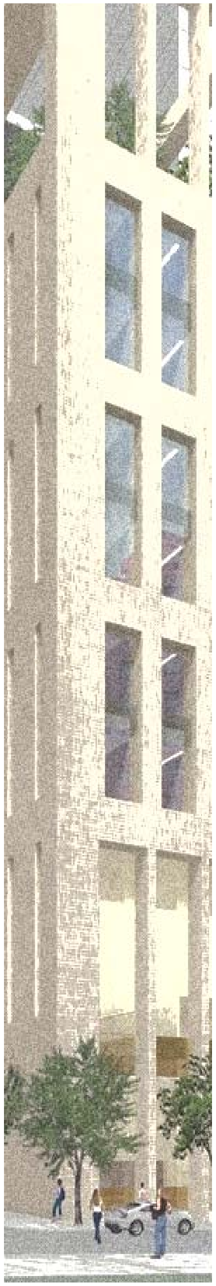
Nominal shear strength of all wall piers sharing a common lateral force shall not exceed:

$$8A_{cv}\sqrt{f'_c}$$

Nominal shear strength of any one pier shall not exceed:

$$10A_{cp}\sqrt{f'_c}$$

Boundary Element Design



Boundary Element Design

Design Criteria & Method
ACI 318-05, 21.7

- Designed for compression zones where max extreme compressive fiber > 0.2f'c.
- Must extend horizontally into web of wall the larger distance of:
  - c – 0.1lw OR c/2
- Locations checked:
  - Each corner of the core, at base level
  - Each end of individual piers adjacent to openings
- BE length and reinforcement (longitudinal & transverse) designed by hand
- Each section checked in PCA column for combined bending/axial strength

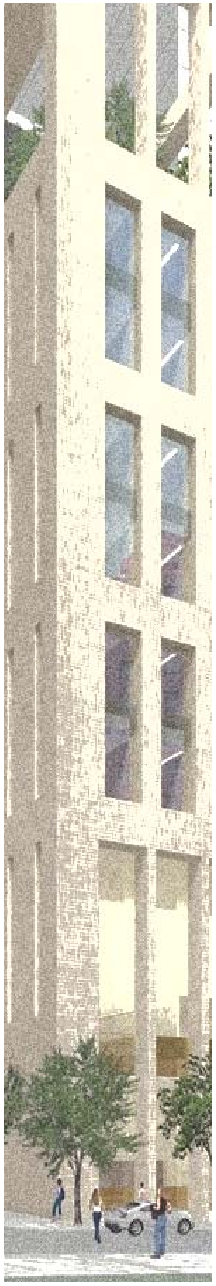
Final Design

- 7 typical BE sections
- Selected reinforcement:

Flexural: (2 curtains) #8 bars, $\rho \geq 1\% \, A_{g\,(BE)}$

Shear/Confinement: #3 hoops & ties @ 4", $A_s \geq 0.44 in^2$ per 4"

Shear Wall Design: Strength



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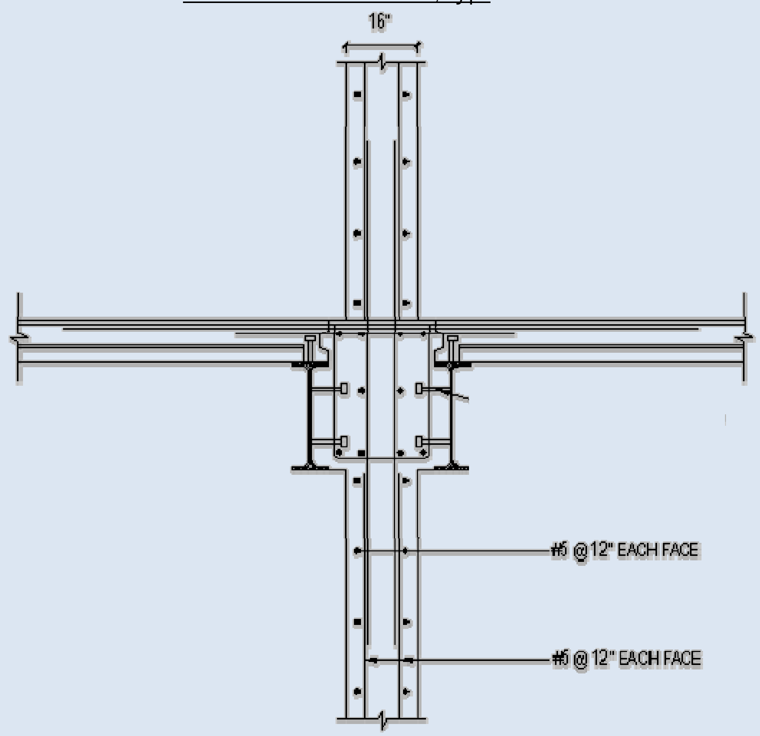
Design for Strength

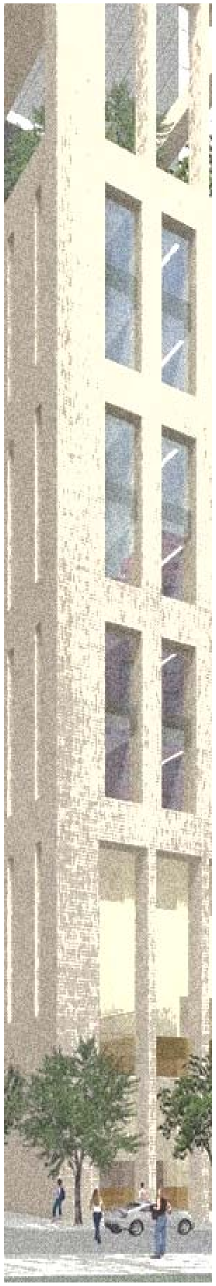
Final Design

Typical Details

- Section at Shear Wall, typ.



Boundary Element Design



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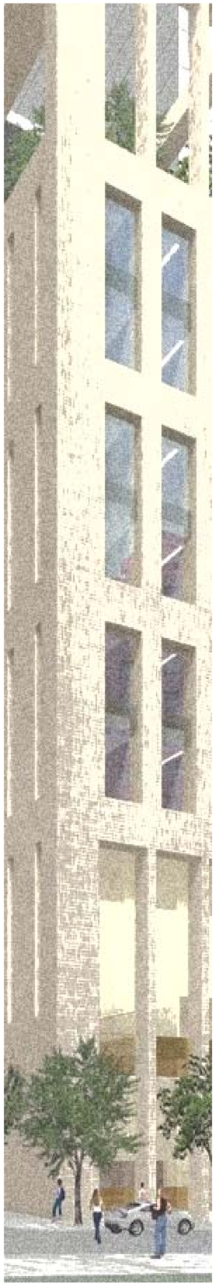
Boundary Element Design

Final Design

Boundary Element Summary

BE #	BE length	BE reinforcement		Steel Required	Steel Provided
BE28	28"	Flexural	(2 curtains) # 8 bars = (8) #8 bars	$\rho = 0.01$	$\rho = 0.033$
		Shear	#3 hoops and ties @ 4" vertical	$A_{st} = 0.3\ in^2$	$A_{st} = 0.44\ in^2$
BE 36	36"	Flexural	(2 curtains) # 8 bars = (10) #8 bars	$\rho = 0.01$	$\rho = 0.014$
		Shear	#3 hoops and ties @ 4" vertical	$A_{st} = 0.3\ in^2$	$A_{st} = 0.44\ in^2$
BE56	56"	Flexural	(2 curtains) # 8 bars = (16) #8 bars	$\rho = 0.01$	$\rho = 0.014$
		Shear	#3 hoops and ties @ 4" vertical	$A_{st} = 0.3\ in^2$	$A_{st} = 0.44\ in^2$
BE28x56	28"x56" (corner)	Flexural	(2 curtains) # 8 bars = (24) #8 bars	$\rho = 0.01$	$\rho = 0.017$
		Shear	#3 hoops and ties @ 4" vertical	$A_{st} = 0.3\ in^2$	$A_{st} = 0.44\ in^2$
BE36x36	36"x36" (corner)	Flexural	(2 curtains) # 8 bars = (21) #8 bars	$\rho = 0.01$	$\rho = 0.023$
		Shear	#3 hoops and ties @ 4" vertical	$A_{st} = 0.3\ in^2$	$A_{st} = 0.44\ in^2$
BE36x56	36"x56" (corner)	Flexural	(2 curtains) # 8 bars = (28) #8 bars	$\rho = 0.01$	$\rho = 0.018$
		Shear	#3 hoops and ties @ 4" vertical	$A_{st} = 0.3\ in^2$	$A_{st} = 0.44\ in^2$
BE60x28	60"x28" (corner)	Flexural	(2 curtains) # 8 bars = (20) #8 bars	$\rho = 0.01$	$\rho = 0.014$
		Shear	#3 hoops and ties @ 4" vertical	$A_{st} = 0.3\ in^2$	$A_{st} = 0.44\ in^2$

Design Implications



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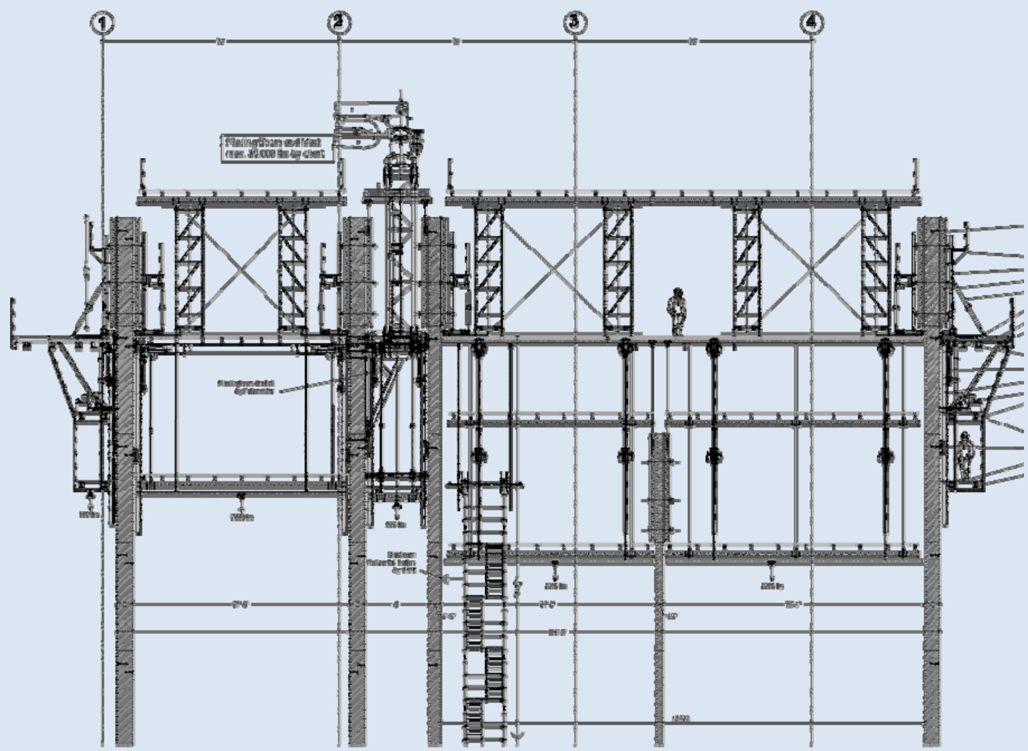
3. Construction Method



Courtesy of PERI Formwork Systems, Inc.