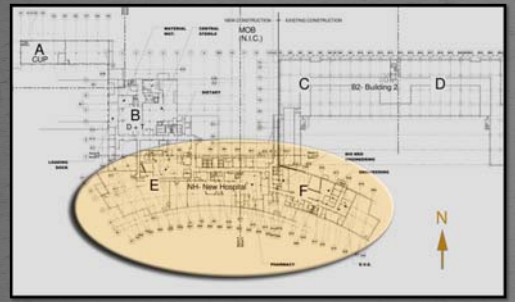
2010 AE Senior Thesis

University Medical Center at Princeton

Presented by: Stephen Perkins
5th year Structural Option
BAE/MAE
Advised by: Dr. Linda Hanagan



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- UMCP consists of three separate facilities
  - Central Utility plant
  - D&T Building
  - New Hospital
- Focus of this thesis is limited to New Hospital
- Building Statistics

Size:	400,000 sq.ft.
Height:	91'-0" above grade
	Design height = 147'-0"
	(Future 4 story addition)
Stories:	6 stories + 1 level below grade
	Typical story height = 14'-0"
Construction start:	May 2009
Construction end:	January 2012
Overall cost (NH):	~$115 million
Delivery method:	Design-Bid-Build

Presentation Outline

- **Introduction**
- Objective/Goals
- Redesign Considerations
  - Structural
  - Architectural
  - Construction
- Structural Depth
  - RAM Model
  - Process
  - Results
- Architectural Breadth
  - Renderings
  - Analysis
- CM Breadth
  - Cost Analysis
  - Schedule Analysis
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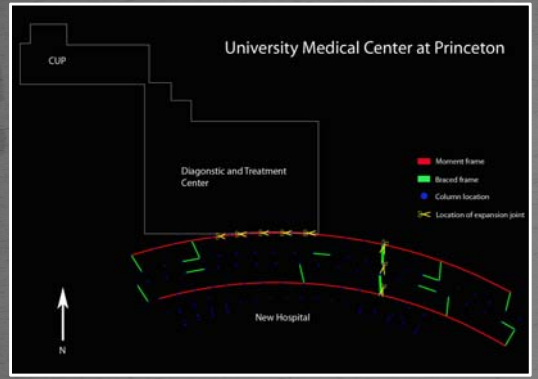
Structural

- Gravity system
  - Composite beam floor system
    - 3-1/4" LWC over 3", 20 Ga. composite metal deck
    - ¾" shear studs, ASTM 108
    - Typical bay size: 30'-0" x 30'-0"; 30'-0" x 18'-0"
    - Typical sizes: W14 columns
      W12-W27 beams/girders
- Lateral system
  - 18 braced frames (9 in each wing)
    - HSS shapes for diagonals
    - Each frame has unique brace configuration
  - 4 moment frames
    - Along north and south facades
    - PR moment connections
- Foundation
  - Primarily spread footings w/ mat foundations in certain areas
  - Tension-only mini piles attached to braced frame footings
    - Extend into bedrock found 8'-30' below ground level

Presentation Outline



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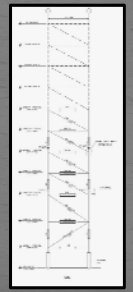

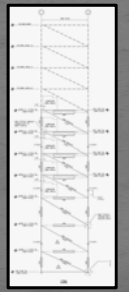

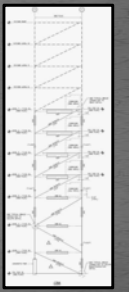

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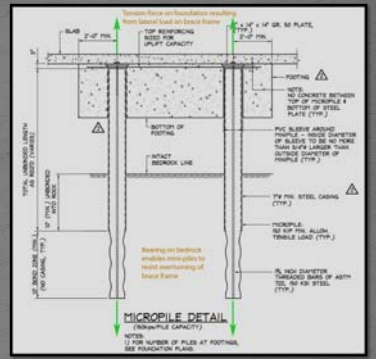

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Architectural

- Curtain wall on south façade is prominent architectural feature
  - 92'-0" tall
  - Insulated glass with low-e coating
  - Glass is tinted at floor levels to hide structure
  - Provides great deal of daylight in patient rooms

- 1st floor is mainly public space
  - Café
  - Lobbies
  - Sensitive equipment areas

- Floors above 2nd floor are private patient areas
  - Rooms located along north and south facades
  - Nurse stations, offices, corridors in middle

1st Floor Plan

Typical Floor Plan

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Goal #1
Eliminate net tension at the foundation level
- ➢ No longer would need tension only mini-piles underneath spread footings

Goal #2
Improve vibration performance of floor system
- ➢ Meet standards established for sensitive equipment

Design Solution
Redesign the structural system in concrete!
- ➢ Would increase compressive force enough to overcome tension from lateral loads
- ➢ Concrete floor systems tend to perform better under vibration than steel floor systems

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Structural considerations...

- Redesign of lateral system → Shear walls, moment frames
- Redesign slab → Two-way flat slab
- Redesign columns → Use same column grid (no floor plan disruption)
- Redesign beams → Only on exterior to support curtain wall; included in moment frames
- Redesign foundation → Spread and continuous footings; mat foundation assumed where necessary

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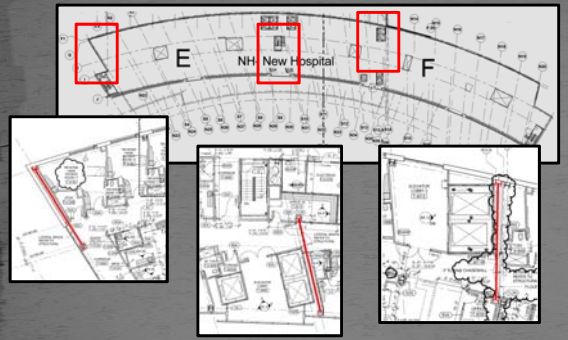

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Architectural considerations….

•Floor plan adjustments ⟶ Careful shear wall placement

•Curtain wall interaction with structure ⟶ Breadth topic

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Construction Management considerations...

- Changes to project cost ⟶ Breadth topic
- Changes to project schedule ⟶ Breadth topic

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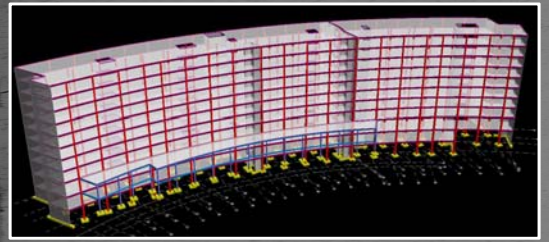

Initial Assumptions

- Expansion joint modeled
- Hospital designed as 10-story building

Modeling Assumptions

- Slab acts as rigid diaphragm
- Columns braced against side sway by shear walls and slab
- Moment frame beams modeled as fixed in order to transfer moment across the frame
- Rigid end zones applied with 50% reduction
- P-Δ effects considered within model
- Shear walls have no stiffness out-of-plane
- Modified moment of inertia...
  - Columns: 0.70Ig
  - Beams: 0.35Ig
  - Walls: 0.35Ig
  - Slab: 0.25Ig

(Per ACI 10.10.4.1)

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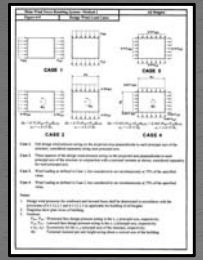

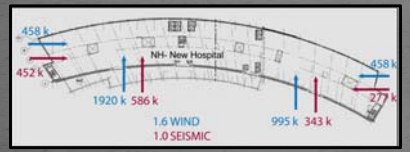

Applied loads

Wind

- Four different load cases to account for variability in wind direction
- These wind cases (8 in total) were calculated by hand and entered manually into RAM model

Seismic

- Fundamental period of both wings exceeded CuTa. Therefore, CuTa was used to determine seismic forces.
- Lateral system defined as special reinforced concrete shear walls
  - R = 6.0
  - Cd = 5.0
- Building weight and seismic loads were calculated by hand to confirm RAM calculation
  - Base shears within 1.0%

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Natural Frequency

$f_n = (c * \emptyset)/a^2$

where $c = [Eh^3/12(1-v^2)]*g/q$

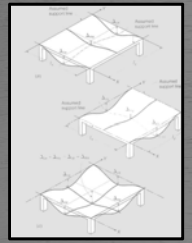
Peak Acceleration

$a_p/g \leq P_o e^{-0.35fn}/\beta W$

Vibration Velocity

$V = U_v \Delta_p / f_n$

where $U_v = \pi F_m f_o^2$



$\Delta total = \Delta midA + \Delta colB$

Floor Vibration

- Initially assumed that slab thickness would be governed by vibration
- Considerations for vibration design:
  1. Source
  2. Transmission path
  3. Floor characteristics
  4. Human sensitivity
  5. Acceptable standards

Vibration Considerations	Description	Value	Units
Source	Walking	2-3	Hz
Transmission path	Mass	W/g	kg-s^2/m
	E	1.25Ec	ksi
	Damping	5%	n/a
Floor Characteristics	Nat. Frequency	f_n	Hz
	Peak Acceleration	a_p/g	n/a
Human Sensitivity	Variable range	4-8	Hz
Acceptable Standards	Humans	0.005	n/a
	Sensitive Equipment	4000	μin/s

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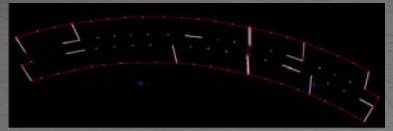
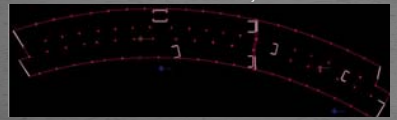
Initial iteration



34th iteration

Final Shear Wall Layout

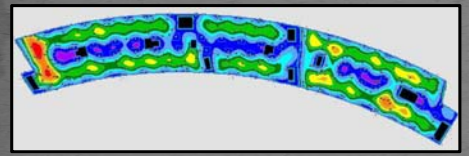


Lateral System Layout

Trial #34				
Wall f c	10 ksi			
Wall thickness	24"			
Slab thickness	10"			
Design Periods				
Direction	West		East	
	Period	Mode	Period	Mode
X	1.682	1	1.314	2
Y	1.308	3	0.719	5
Z	0.941	4	0.585	6

Final Iteration				
Wall f c	8 ksi			
Wall thickness	12"			
Slab thickness	8"			
Design Periods				
Direction	West		East	
	Period	Mode	Period	Mode
X	2.810	2	3.763	1
Y	2.033	3	1.865	4
Z	1.431	5	1.100	6

Presentation Outline



Check assumed behavior

Slab Deflection

Dead Load Deflection				
Δ_{foilD}	Δ_{fmidA}	Δ_{max}	$\Delta_{concept}$	% Diff
(in.)				
0.160	0.034	0.194	0.180	7.8

Dead + Live Load Deflection				
Δ_{foilD}	Δ_{fmidA}	Δ_{max}	$\Delta_{concept}$	% Diff
(in.)				
0.304	0.065	0.369	0.350	5.4

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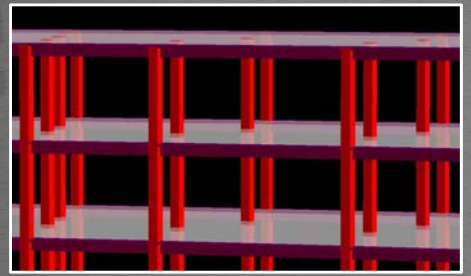
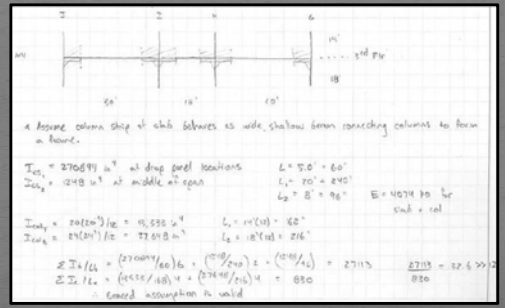


Check assumed behavior

Non-Sway Columns



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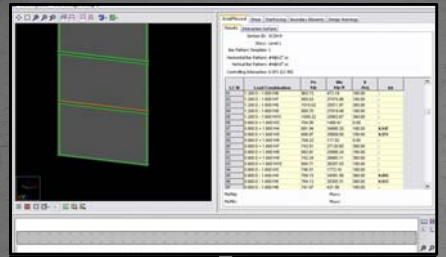

Wall Design

Thickness = 12”
f'c = 8 ksi
Typical reinforcing:
Horizontal- #4 @ 12” o.c.
Vertical- #6 @ 10” o.c.

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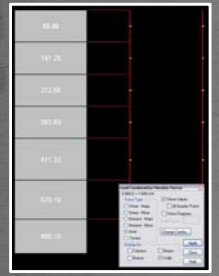

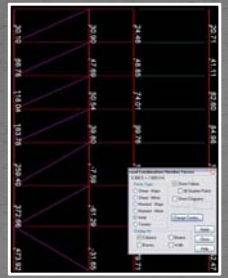

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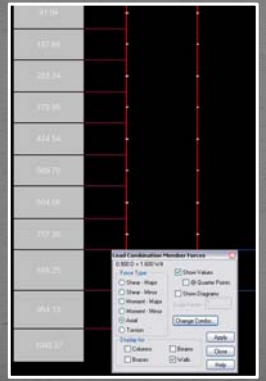

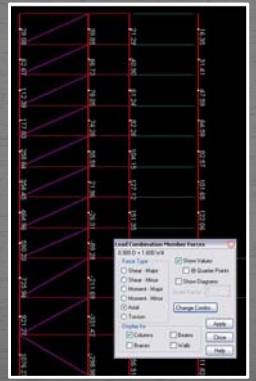

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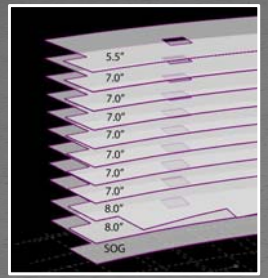

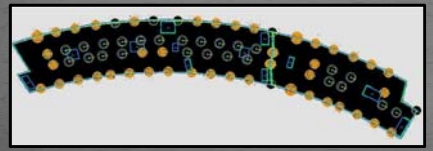

Slab Design

8" slab

Vibration for Sensitive Equipment					Vibration for Walking	
Velocity	Walking Rate				a_p/g	0.0011
	Fast	Medium	Slow			0.0025 operating
V	3991.89	887.09	238.45	4000 operating		0.005 offices

7" slab

Vibration for Sensitive Equipment					Vibration for Walking	
Velocity	Walking Rate				a_p/g	0.0018
	Fast	Medium	Slow			0.0025 operating
V	6706.69	1490.38	400.61	4000 operating		0.005 offices

Composite Beam

Vibration for Sensitive Equipment					Vibration for Walking	
Velocity	Walking Rate				a_p/g	0.0023
	Fast	Medium	Slow			0.0025 operating
V	43000.00	9502.00	2554.00	4000 operating		0.005 offices

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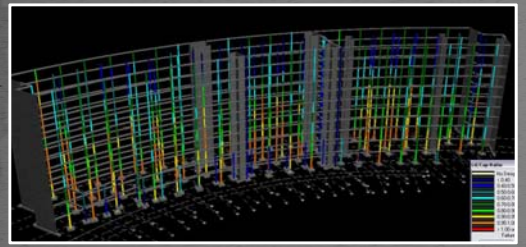

Column Design

Stories 1-4: 24"x24"
Stories 5-7: 20"x20"
Addition: 18"x18"
f'c = 5 ksi
Typical reinforcing:
- 20 bars (6x4)
- 24 bars (7x5)
- 28 bars (8x6)

Longitudinal: #5-#8 bars
Transverse: #4 bars

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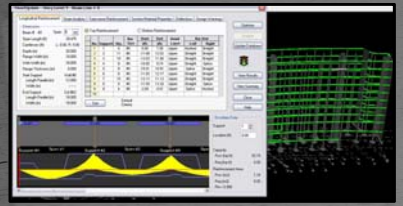

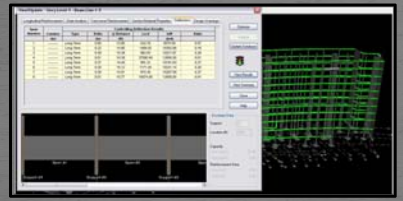

Beam Design

Size: 18" x 20"
f'c = 5 ksi
Typical reinforcing:
#7 - #11 bars

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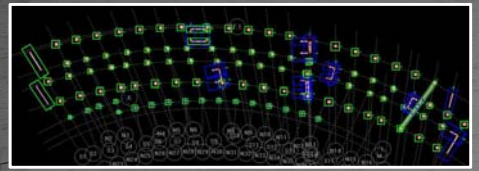
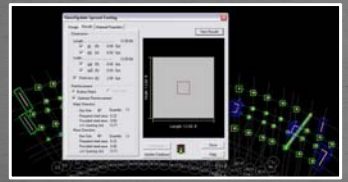
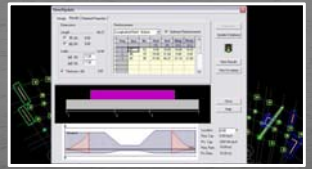




Foundation Design

Size: 7' x 7' interior spread footings
10' x 10' exterior spread footings
15' wide continuous walls footings
f'c = 3 ksi
Typical reinforcing:
#7 - #11 bars



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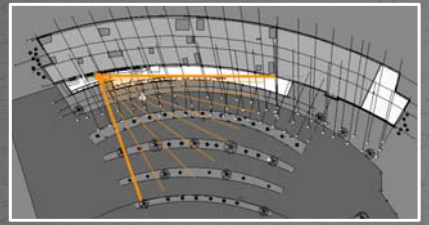

Interior Lobby-Steel Design

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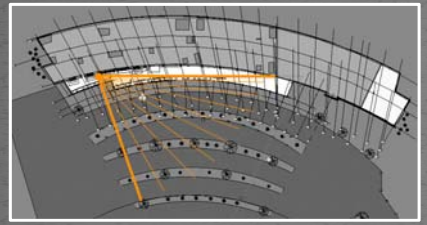

Interior Lobby-Concrete Design

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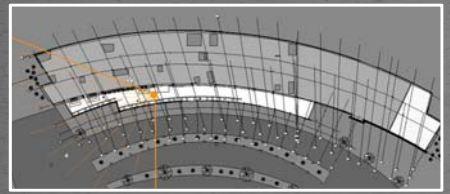
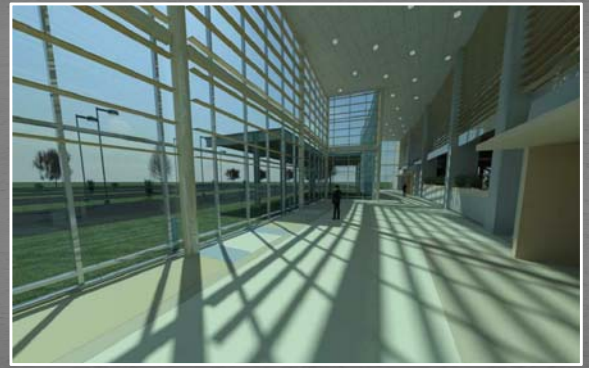


Interior Lobby-Steel Design



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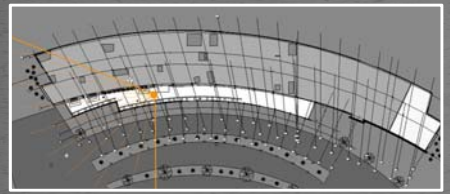

Interior Lobby-Concrete Design

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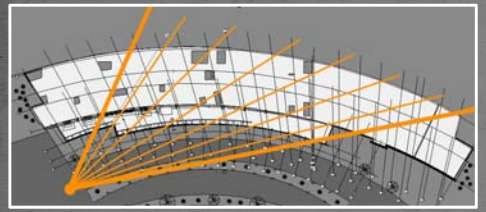
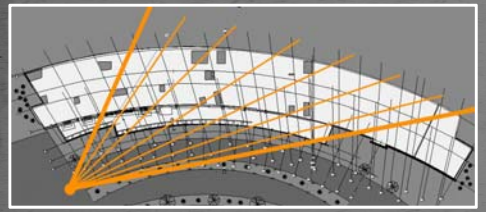


Exterior-Steel Design

Presentation Outline

Exterior-Concrete Design



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Cost Analysis- Steel

Structural Framing Schedule			RS Means 2010				
Family and Type	Count	Length (ft.)	Units	Material	Labor	Equipment	Total Cost
HSS8X8X1/4	3	86	Each	645	51	32	$ 2,184.00
HSS8X8X5/16	6	192	Each	645	51	32	$ 4,368.00
HSS8X8X.375	2	46	Each	645	51	32	$ 1,456.00
HSS10X4X3/8	34	443	Each	645	51	32	$ 24,752.00
HSS10X8X1/2	9	238	Each	645	51	32	$ 6,552.00
HSS10X8X3/8	20	528	Each	645	51	32	$ 14,560.00
HSS10X8X5/16	3	93	Each	645	51	32	$ 2,184.00
HSS10X10X1/2	7	222	Each	645	51	32	$ 5,096.00
HSS10X10X3/8	8	257	Each	645	51	32	$ 5,824.00
HSS12X4X3/8	1	24	Each	645	51	32	$ 728.00
HSS12X8X1/2	4	126	Each	645	51	32	$ 2,912.00
HSS12X8X3/8	6	192	Each	645	51	32	$ 4,368.00
HSS12X10X1/2	10	327	Each	645	51	32	$ 7,280.00
HSS12X10X3/8	20	671	Each	645	51	32	$ 14,560.00
HSS12X12X1/2	46	1498	Each	645	51	32	$ 33,488.00
HSS14X4X3/8	2	38	Each	645	51	32	$ 1,456.00
HSS14X6X3/8	1	19	Each	645	51	32	$ 728.00
HSS16X8X3/8	10	166	Each	645	51	32	$ 7,280.00
HSS16X8X5/16	3	94	Each	645	51	32	$ 2,184.00
HSS20X8X3/8	2	33	Each	645	51	32	$ 1,456.00
HSS20X12X1/2	10	291	Each	645	51	32	$ 7,280.00
W-Wide Flange: W8X10	182	2417	LF	$12.10	$4.26	$2.68	$ 46,019.68
W-Wide Flange: W8X40	30	822	LF	$58.00	$4.64	$2.92	$ 53,890.32
W-Wide Flange: W12X14	15	21	LF	$19.35	$2.90	$1.83	$ 505.68
W-Wide Flange: W12X19	620	9645	LF	$26.50	$2.90	$1.83	$ 301,213.35
W-Wide Flange: W12X26	6	57	LF	$31.50	$2.90	$1.83	$ 2,065.11
W-Wide Flange: W12X35	40	538	LF	$42.50	$3.15	$1.98	$ 25,624.94
W-Wide Flange: W12X40	5	94	LF	$60.50	$3.41	$2.14	$ 6,208.70
W-Wide Flange: W14X22	125	2411	LF	$31.50	$2.58	$1.62	$ 86,072.70
W-Wide Flange: W16X26	696	20067	LF	$31.50	$2.55	$1.61	$ 715,589.22
W-Wide Flange: W16X31	64	1857	LF	$37.50	$2.84	$1.79	$ 78,235.41
W-Wide Flange: W18X35	164	4846	LF	$42.50	$3.85	$1.83	$ 233,480.28
W-Wide Flange: W18X40	35	972	LF	$48.50	$3.85	$1.83	$ 52,662.96
W-Wide Flange: W21X44	194	5349	LF	$53.00	$3.47	$1.65	$ 310,883.88
W-Wide Flange: W21X50	38	1152	LF	$60.50	$3.47	$1.65	$ 75,594.24
W-Wide Flange: W21X55	2	63	LF	$75.00	$3.57	$1.69	$ 5,056.38
W-Wide Flange: W24X55	206	6104	LF	$66.50	$3.33	$1.58	$ 435,886.64
W-Wide Flange: W24X62	10	336	LF	$75.00	$3.33	$1.58	$ 26,849.76
W-Wide Flange: W24X68	56	1682	LF	$82.50	$3.33	$1.58	$ 147,023.62
W-Wide Flange: W24X76	22	722	LF	$92.00	$3.33	$1.58	$ 69,969.02
W-Wide Flange: W24X104	20	228	LF	$126.00	$3.52	$1.67	$ 29,911.32
W-Wide Flange: W27X84	64	2080	LF	$102.00	$3.11	$1.47	$ 221,686.40
W-Wide Flange: W30X90	3	97	LF	$120.00	$3.08	$1.46	$ 12,080.38
W-Wide Flange: W30X99	8	300	LF	$120.00	$3.08	$1.46	$ 37,362.00
W-Wide Flange: W30X108	3	103	LF	$131.00	$3.08	$1.46	$ 13,960.62
W-Wide Flange: W30X116	4	136	LF	$140.00	$3.19	$1.51	$ 19,679.20
W-Wide Flange: W33X118	2	66	LF	$143.00	$3.14	$1.49	$ 9,743.58
W-Wide Flange: W33X130	2	69	LF	$157.00	$3.26	$1.55	$ 11,164.89
W-Wide Flange: W33X141	2	74	LF	$171.00	$3.26	$1.55	$ 13,009.94
W-Wide Flange: W36X302	1	37	LF	$365.00	$3.57	$1.69	$ 13,699.62
W-Wide Flange: W36X652	1	31	LF	$365.00	$3.57	$1.69	$ 11,478.06
Totals	2827	67995					$ 3,217,303.90

Structural Column Schedule			RS Means 2010				
Family and Type	Length (ft.)	Count	Units	Material	Labor	Equipment	Total Cost
HSS-Column: HSS14X0.500	753	20	Each	$ 1,300.00	$ 57.00	$ 35.50	$ 27,850.00
W-Wide Flange-Column: W12X72	407	22	LF	$ 105.00	$ 2.60	$ 1.63	$ 44,456.61
W-Wide Flange-Column: W14X90	1366.5	53	LF	$ 145.00	$ 2.66	$ 1.67	$ 204,059.45
W-Wide Flange-Column: W14X99	1369.5	49	LF	$ 145.00	$ 2.66	$ 1.67	$ 204,507.44
W-Wide Flange-Column: W14X109	616	22	LF	$ 145.00	$ 2.66	$ 1.67	$ 91,987.28
W-Wide Flange-Column: W14X120	590.16	18	LF	$ 145.00	$ 2.66	$ 1.67	$ 88,128.59
W-Wide Flange-Column: W14X132	1894.7	66	LF	$ 145.00	$ 2.66	$ 1.67	$ 282,935.55
W-Wide Flange-Column: W14X145	1868.36	62	LF	$ 213.00	$ 2.80	$ 1.76	$ 406,480.40
W-Wide Flange-Column: W14X159	435.49	13	LF	$ 213.00	$ 2.80	$ 1.76	$ 94,745.20
W-Wide Flange-Column: W14X176	927.66	25	LF	$ 213.00	$ 2.80	$ 1.76	$ 201,821.71
W-Wide Flange-Column: W14X193	38.67	2	LF	$ 213.00	$ 2.80	$ 1.76	$ 8,413.05
W-Wide Flange-Column: W14X311	593.67	23	LF	$ 213.00	$ 2.80	$ 1.76	$ 129,158.85
W-Wide Flange-Column: W14X342	931.34	34	LF	$ 213.00	$ 2.80	$ 1.76	$ 202,622.33
Totals	11792	469					$1,987,166.45

Floor/Roof Schedule				RS Means 2010								
Family and Type	Level	Volume (cu. ft.)	Area (sq. ft.)	Units	Deck			Units	Concrete			Total Cost
					Material	Labor	Equipment		Material	Labor	Equipment	
Floor: Lobby Floor	Level 1	25331.35	41928	SF	$ 1.50	$ 0.51	$ 0.05	CY	$ 109.00	$ 11.75	$ 35.25	$ 232,730.59
Floor: LWConcrete on Metal Deck	Level 2	24262.65	46584	SF	$ 1.50	$ 0.51	$ 0.05	CY	$ 109.00	$ 11.75	$ 35.25	$ 236,147.24
Floor: LWConcrete on Metal Deck	Level 3	23960.23	46004	SF	$ 1.50	$ 0.51	$ 0.05	CY	$ 109.00	$ 11.75	$ 35.25	$ 233,205.12
Floor: LWConcrete on Metal Deck	Level 4	24138.17	46345	SF	$ 1.50	$ 0.51	$ 0.05	CY	$ 109.00	$ 11.75	$ 35.25	$ 234,935.68
Floor: LWConcrete on Metal Deck	Level 5	24137.61	46344	SF	$ 1.50	$ 0.51	$ 0.05	CY	$ 109.00	$ 11.75	$ 35.25	$ 234,930.39
Floor: LWConcrete on Metal Deck	Level 6	24032.28	46142	SF	$ 1.50	$ 0.51	$ 0.05	CY	$ 109.00	$ 11.75	$ 35.25	$ 233,905.69
Basic Roof: S1	Level 3	4793.83	9204	SF	$ 1.37	$ 0.38	$ 0.04	CY	$ 109.00	$ 11.75	$ 35.25	$ 44,172.84
Basic Roof: S2	T/Parapet	40050.72	50590	SF	$ 1.37	$ 0.38	$ 0.04	CY	$ 109.00	$ 11.75	$ 35.25	$ 321,960.26
Totals		190707	333141									$ 1,771,987.82

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Cost Analysis- Concrete

Structural Beam Schedule				RS Means 2010													
				Formwork				Concrete				Reinforcing					
Type	Length (ft.)	Area (sq. ft)	Volume (CY)	Units	Material	Labor	Equipment	Units	Material	Labor	Equipment	Type	Weight (tons)	Units	Material	Labor	Equipment	Total Cost
16" x 20"	1432	6207	117.9	SF	$ 1.43	$ 8.65	$ -	CY	$ 109.00	$ 39.50	$ 19.85	#7 and below	80.00	Ton	$ 800.00	$ 953.00	$ -	$ 253,658.80
18" x 20"	8566	39039	774.32	SF	$ 1.43	$ 8.65	$ -	CY	$ 109.00	$ 39.50	$ 19.85							$ 852,021.31
																		$ 815,630.42

Shear Wall Schedule				RS Means 2010													
				Formwork				Concrete				Reinforcing					
Type	Length (ft.)	Area (sq. ft)	Volume (CY)	Units	Material	Labor	Equipment	Units	Material	Labor	Equipment	Type	Weight (tons)	Units	Material	Labor	Equipment	Total Cost
12" - #6@6	1432	131922	2443	SF	$ 1.43	$ 8.65	$ -	CY	$ 109.00	$ 39.50	$ 19.85	#7 and below	98.00	Ton	$ 800.00	$ 953.00	$ -	$ 2,174,926.81
																		$ 2,174,926.81

Structural Column Schedule					RS Means 2010													
					Formwork				Concrete				Reinforcing					
Family and Type	Length (ft.)	Area (sq. ft)	Volume (CY)	Count	Units	Material	Labor	Equipment	Units	Material	Labor	Equipment	Type	Weight (tons)	Units	Material	Labor	Equipment	Total Cost
20" x20" square	3318	658.9	141.35	237	SF	$ 2.28	$ 6.65	$ -	CY	$ 109.00	$ 37.00	$ 18.45	#7 and below	174.00	Ton	$ 800.00	$ 1,000.00	$ -	$ 566,906.11
24" x24" square	5092	1204	754.44	301	SF	$ 2.28	$ 6.65	$ -	CY	$ 109.00	$ 37.00	$ 18.45	#8 and above	38.30	Ton	$ 800.00	$ 650.00	$ -	$ 543,375.14
22" dia. circular	569	129.20	58.52	34	LF	$ 8.15	$ 9.70	$ -	CY	$ 109.00	$ 37.00	$ 18.45							$ 20,315.76
Totals	12357			469														$ 1,130,597.02

Floor/Roof Schedule				RS Means 2010							
					Formwork				Concrete		
Family and Type	Level	Volume (cu. ft.)	Area (sq. ft.)	Units	Material	Labor	Equipment	Units	Material	Labor	Equipment	Total Cost
8" Two-Way Flat Slab	Level 1	27932	41928	SF	$ 4.43	$ 4.33	$ -	CY	$ 109.00	$ 11.75	$ 35.25	$ 528,780.72
8" Two-Way Flat Slab	Level 2	31056	46584	SF	$ 4.43	$ 4.33	$ -	CY	$ 109.00	$ 11.75	$ 35.25	$ 587,510.51
7" Two-Way Flat Slab	Level 3	26836	46004	SF	$ 4.43	$ 4.33	$ -	CY	$ 109.00	$ 11.75	$ 35.25	$ 538,045.56
7" Two-Way Flat Slab	Level 4	27035	46345	SF	$ 4.43	$ 4.33	$ -	CY	$ 109.00	$ 11.75	$ 35.25	$ 562,182.01
7" Two-Way Flat Slab	Level 5	27034	46344	SF	$ 4.43	$ 4.33	$ -	CY	$ 109.00	$ 11.75	$ 35.25	$ 562,169.88
7" Two-Way Flat Slab	Level 6	26916	46142	SF	$ 4.43	$ 4.33	$ -	CY	$ 109.00	$ 11.75	$ 35.25	$ 559,719.55
7" Two-Way Flat Slab	Level 3	5369	9204	SF	$ 4.43	$ 4.33	$ -	CY	$ 1.37	$ 0.38	$ 0.04	$ 80,982.98
7" Two-Way Flat Slab	T/Parapet	29511	50590	SF	$ 4.43	$ 4.33	$ -	CY	$ 1.37	$ 0.38	$ 0.04	$ 445,124.86
Totals		201708	333141									$ 3,884,525.08

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Cost Comparison

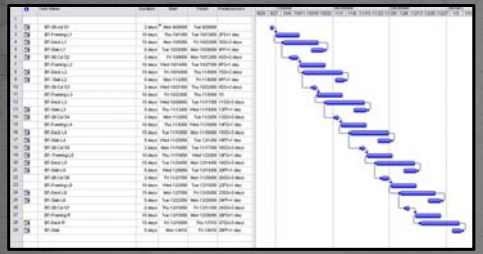
Structural System Cost		
Original Steel Design		
Slabs	$	1,771,988
Columns	$	1,987,166
Framing	$	3,217,304
Total	**$**	**6,976,458**

Structural System Cost		
Concrete Redesign		
Slabs	$	3,884,525
Columns	$	1,130,597
Framing	$	835,630
Walls	$	2,174,927
Total	**$**	**8,025,679**

Presentation Outline

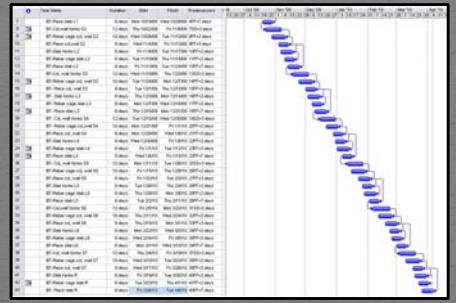
Schedule Comparison

Steel



Total = 102 days

Concrete



Total = 189 days

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Conclusion

Goal #1
Eliminate net tension at the foundation level
- ➢No longer would need tension only mini-piles underneath spread footings

Goal Accomplished!

Goal #2
Improve vibration performance of floor system
- ➢Meet standards established for sensitive equipment

Goal Accomplished!

Recommendations

- •A concrete redesign can not be recommended at this point
  - •Uncertainty due to **cost**
  - •Uncertainty due to **schedule**
  - •Uncertainty due to **architecture**

Presentation Outline

Acknowledgements

Princeton Health Care System

Turner Construction
Chris Auer
Miles Cava

Penn State AE Faculty/Staff
Dr. Linda Hanagan
Dr. Andres Lepage
Dr. Louis Geschwinder
Dr. Ali Memari
Prof. Parfitt
Prof. Holland
Corey Wilkinson

O'Donnell & Naccarato Structural Engineers
Michael Miller

Severud Associates
Steve Reichwein
Matthew Peitz

McNamara/Salvia Inc.
Bob McNamara

My parents!

My friends!

My fellow classmates!

Thank you for listening!

Presentation Outline