Washington Park Condominiums
Mt. Lebanon, Pennsylvania

Benjamin Follett
Structural Option
Architectural Engineering
Senior Thesis Presentation 2009
The Pennsylvania State University

Presentation Outline

- Project Overview
- Existing Structural System
- Why Redesign
- Structural Redesign
- Architectural Detail Study
- Acoustics Study
- Conclusions
- Questions

Project Overview

Location: Mt. Lebanon, Pennsylvania

Building Type: Multi-Use (Residential/Retail)

Size: 148,000 sq. ft.

Project Cost: $23,418,000

Delivery Method: Design-Bid-Build

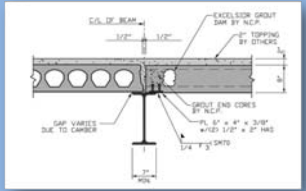
Owner: Zamagias Properties

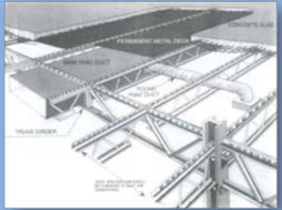
Construction Dates: Fall 2008-Fall 2010

Existing Conditions – Floor Systems

Existing Floor Systems

- 8" Precast Concrete Plank (Basement thru Floor 2)
- VESCOM Composite Joist with 3 5/8" concrete slab (Floors 3 thru 8)
- Steel Beams and Columns





Existing Conditions – Lateral System

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Structural Redesign
Architectural Detailing
Acoustics
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Questions

Steel Moment Frames

- 17 moment frames per floor
  - 6 exterior
  - 11 interior
- Comprised of special joist Girders designed by VESCOM in East-West Direction
- W-shapes used in North-South Direction
- VESCOM floor system used as a rigid diaphragm to transfer loading

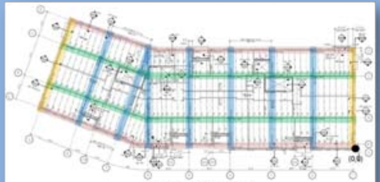
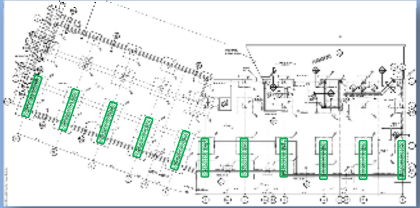


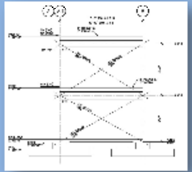
Figure 1: Moment Frame Diagram

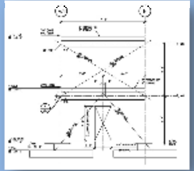
Existing Conditions – Lateral System

Steel Brace Frames

- 11 frames in the sub-basement level
- HSS 8x8x1/2 and HSS 6x6x3/8
- Primary function is to resist lateral soil pressure







Why Redesign?

Problem Statement

- Lack of construction experience with newer composite steel joist system
- Inefficient lateral system with most columns and beams being part of the moment frame system
- Possibility of unwanted floor vibrations with use of composite joist system.
- Ultimately why was composite joist system chosen over a reinforced concrete system?

Problem Solution – Complete redesign of both the gravity and lateral systems of Washington Park Condominiums

Why Redesign?

Design Goals

- Study and determine relevant differences between the use of steel and concrete structures for Washington Park Condominiums
- Maintain allowable story drift while reducing motion perceived by building occupants
- Adhere to the current column layout of the building
- Design a more efficient lateral force resisting system using concrete
- Reduce sound transmission throughout building between areas with high noise levels and the apartments

Learn how to design both gravity and lateral systems using reinforced concrete.

Structural Redesign – Gravity System

Two Way Flat Plate

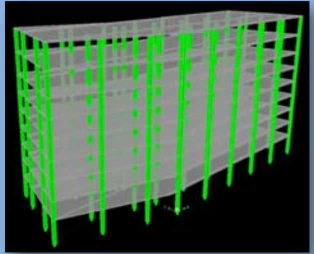
- Analysis/Design
    - PCASlab & Hand Calculations
- Slab Thickness
- Two Way Reinforcement
    - Flexural & Shear
- Deflections

Reinforced Concrete Columns

- Placement and Reinforcement

Foundations

- Sizing and Overturning check



Structural Redesign – Gravity System

Two Way Flat Plate Slab

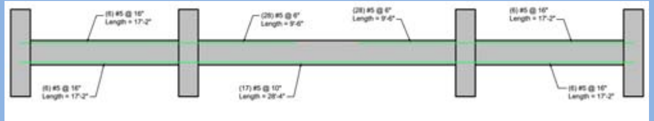
- 10” Slab Thickness using ACI 318-08
- Typical bays are 28’-0” x 28’-0” and 28’-0” x 17’-2” bays
- Controlling load case = 1.2D + 1.6L +0.8W
- For hand calculations only interior bays were checked
- Reinforcement using Direct Design Method

Two Way Flat Plate Slab

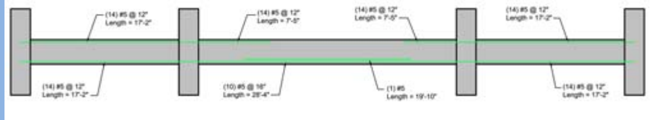
Interior Slab - Hand Calculations		Interior Slab - PCASlab		Long Interior Slab – Reinforcement		Long Interior Slab - Reinforcement	
M^- (CS)	#5 @ 5.5" O/C	M^- (CS)	(28) #5 @ 6" O/C	M^- (CS)	#5 @ 6" O/C	M^- (CS)	(29) #5 @ 5.5" O/C
M^+ (CS)	#5 @ 14" O/C	M^+ (CS)	(17) #5 @ 10" O/C	M^+ (CS)	#5 @ 14" O/C	M^+ (CS)	(10) #5 @ 16" O/C
M^- (MS)	#5 @ 15.25" O/C	M^- (MS)	(10) #5 @ 16" O/C	M^- (MS)	#5 @ 15.75" O/C	M^- (MS)	(10) #5 @ 16" O/C
M^+ (MS)	#5 @ 15.25" O/C	M^+ (MS)	(14) #5 @ 12" O/C	M^+ (MS)	#5 @ 15.75" O/C	M^+ (MS)	(8) #5 @ 16" O/C

Shear Capacity in Slab			Shear Reinforcement	
V_u	52.41	OK	Bar/Wire Limit - V_c	244.19
ϕV_c	142.44		$V_u \le V_c$	USE BAR/WIRE
Punching Shear Capacity in Slab			V_s	188.68
V_u	222.9051	NO GOOD	s = d/2	4.5
ϕV_c	128.7158		A_v	1.57
			Use (15) #3 Stirrups @ 4.5"	

Two Way Flat Plate Slab



Column Strip Flexural Reinforcement



Middle Strip Flexural Reinforcement

Two Way Flat Plate Slab – Deflections

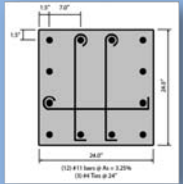
- Allowable deflections from ACI 9.5
- All slab deflections meet given criteria

Deflections for Two Way Slabs				
	Interior Span (Short Direction)	Exterior Span (Short Direction)	Interior Span (Long Direction)	Exterior Span (Long Direction)
Allowable Live Load Deflection	l/360 = 0.944 in	l/360 = 0.944 in	l/360 = 0.933 in	l/360 = 0.944 in
Actual Live Load Deflection	0.111 in	0.139 in	0.149 in	0.118 in
Allowable Total Load Deflection	l/240 = 1.417 in	l/240 = 1.417 in	l/240 = 1.417 in	l/240 = 1.417 in
Actual Total Load Deflection	0.326 in	0.412 in	0.421 in	0.353 in

Structural Redesign – Gravity System

Reinforced Concrete Columns

- All interior columns designed as gravity only columns
- All columns sized at 24" x 24"
- Loading determined using gravity load take downs
- Reinforcement designed using PCAColumn and hand calculations



Type	Flexural Reinforcement	Shear Reinf.		Transverse Reinforcement
		Av_{min}	0.240	
Interior	(12) #11 @ 7"	None		Use (3) #4 Ties @ 24" throughout

Structural Redesign – Foundations

Foundation Considerations

$$\text{Overturning Factor of Safety} = \frac{\text{Resisting Moment}}{\text{Overturning Moment}}$$

Uplift Check - Shear Wall (Wind)								
	Overturning Moment (k-ft)	Wall Length (ft)	Wall Weight (kips)	Axial Load on Wall (kips)	Resisting Moment (k-ft)	Factor of Safety (Calculated)	Factor of Safety (Recommended)	Uplift Problem
ST2	3127.59	19.5	422.66	981.9	13694.0	4.38	3.0	No
SL2	1385.26	10	216.75	619.7	4182.1	3.02	3.0	No

Uplift Check - Shear Wall (Wind)								
	Overturning Moment (k-ft)	Wall Length (ft)	Wall Weight (kips)	Axial Load on Wall (kips)	Resisting Moment (k-ft)	Factor of Safety (Calculated)	Factor of Safety (Recommended)	Uplift Problem
ST2	2543.45	19.5	422.66	981.9	13694.0	5.38	3.0	No
SL2	715.11	10	216.75	619.7	4182.1	5.85	3.0	No

Foundation Considerations

$$Overturning\ Factor\ of\ Safety = \frac{Resisting\ Moment}{Overturning\ Moment}$$

Spread Footing Sizes			
Type	Existing Design	EnerCalc Design	Optimized Design
Interior Col	12'-0" x 12'-0"	13'-0" x 13'-0"	13'-0" x 13'-0"
Corner Column (C55)	11'-0" x 11'-0"	7'-0" x 7'-0"	11'-0" x 11'-0"
Exterior Column (C65)	8'-0 x 8'-0"	9'-6" x 9'-6"	9'-6" x 9'-6"
Exterior Column (C80)	13'-0" x 13'-0"	8'-6" x 8'-6"	13'-0" x 13'-0"

Structural Redesign – Lateral System

Shear Walls

- Analysis/Design
  - ETABS, PCAColumn & Hand Calculations
- Reinforcement
  - Flexural, Shear and Transverse

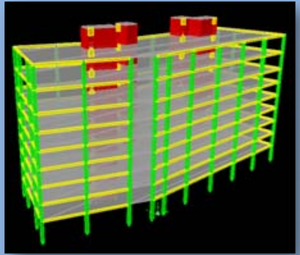
Coupling Beams

- Size and Reinforcement

Modal Analysis

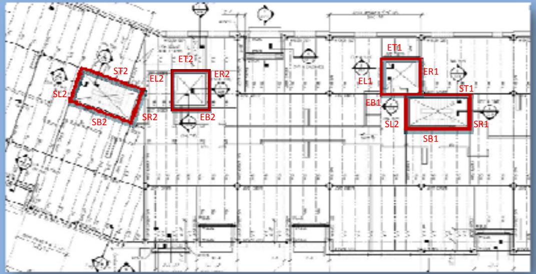
Concrete Moment Frame

- Columns and Beams
  - Size and Reinforcement



Reinforced Concrete Shear Walls

- Placement of Shear Walls around Stair and Elevator Shafts



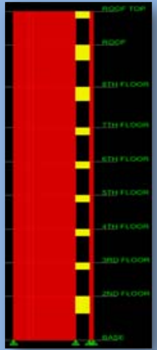
Structural Redesign – Lateral System

Reinforced Concrete Shear Walls

- Trial size of 18” thick walls determined
- Hand Calculations and ETABS used for analysis
- PCAColumn used for design

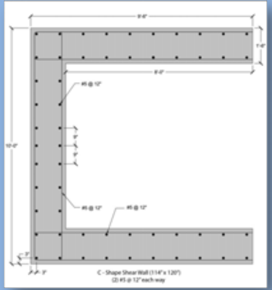
ETABS Analysis

- Wind and Seismic Assumptions (ACI 10.10.4.1)
- f_{22} = 0.7 (Shear Walls)
- I_3 = 0.35 (Coupling Beams)
- Area = 1.0A_g (Both)
- Rigid diaphragm modeled to transfer loading
- Controlling Load Case = 1.2D + 1.6W + 1.0L + 0.5S
- Torsion considered using 5% eccentricity



Reinforced Concrete Shear Walls

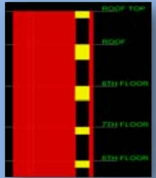
- Each Wall designed as C-shape since all were part of a shaft
- Reinforcement designed using PCAColumn and hand calculations
- Final design (2) #5 @ 12” for shear and flexural reinforcement



Shear Wall Reinforcement Designs		
Shear Walls	Flexural	Shear
SL1, SR1, SL2 & SR2	(2) #5 @ 12"	(2) #5 @ 12"
ER1 & EL1	(2) #5 @ 12"	(2) #5 @ 12"
EB2, ER2, EL2 & ET2	(2) #5 @ 12"	(2) #5 @ 12"
EB1 & ET1	(2) #5 @ 12"	(2) #5 @ 12"
SB1, ST1, SB2 & ST2	(2) #5 @ 12"	(2) #5 @ 12"

Reinforced Concrete Coupling Beams

- Controlling Loads found using ETABS
- Designed to crack before the shear walls and act as plastic hinges
- Designed as 18" thick
- No diagonal reinforcement needed per ACI 21.9.7
- Beams designed as regular and deep beams



Stair Coupling Beams										
Story	l_n (in)	h (in)	A_{cw}	V_n	d	As_{min}	Av_{min}	Flexural Reinf.	Shear Reinf.	Skin Reinf.
Roof	40	58	1044	264.113	55	4.400	0.495	(3) #8 @ 6" T & B	(2) Legs of #5 @ 11"	#4 @ 6.5"
8th	40	54	972	614.747	51	4.080	0.459	(3) #8 @ 6" T & B	(2) Legs of #5 @ 11"	#4 @ 6.5"
2nd -7th	40	26	468	295.989	23	1.840	0.320	(3) #5 @ 6" T & B	(2) Legs of #4 @ 16"	None
1st	40	66	1188	751.357	63	5.040	0.567	(3) #9 @ 6" T & B	(2) Legs of #5 @ 11"	#4 @ 6.5"

Structural Redesign – Lateral System

Reinforced Concrete Coupling Beams

- Controlling Loads found using ETABS
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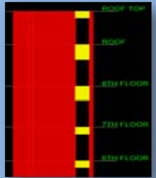
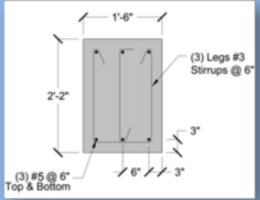


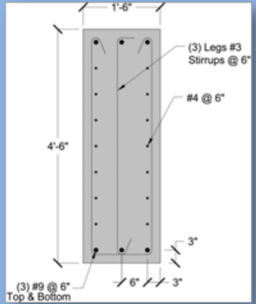
Elevator Coupling Beams										
Story	l_n (in)	h (in)	A_{cw}	V_n	d	As_{min}	Av_{min}	Flexural Reinf.	Shear Reinf.	Skin Reinf.
ROOF	46	58	1044	660.284	55	4.400	0.495	(3) #8 @ 6" T & B	(2) Legs of #5 @ 11"	#4 @ 6"
8th	46	54	972	614.747	51	4.080	0.459	(3) #8 @ 6" T & B	(2) Legs of #5 @ 11"	#4 @ 6"
2nd - 7th	46	26	468	295.989	23	1.840	0.320	(3) #5 @ 6" T & B	(2) Legs of #4 @ 16"	None
1st	46	66	1188	751.357	63	5.040	0.567	(3) #9 @ 6" T & B	(2) Legs of #5 @ 11"	#4 @ 6"

Structural Redesign – Lateral System

Reinforced Concrete Coupling Beams

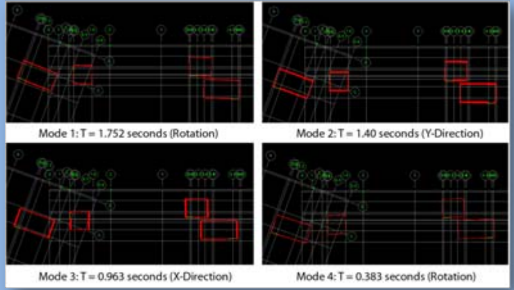
- Typical Beam Sections
- Regular beams and deep beams (≥ 36” deep)
- Deep beams require skin reinforcement





Mode Shapes & Period

- Code determined period, T = 1.046 seconds



Torsional Amplification

- Additional torsional considerations because of building's difference in center of mass and rigidity
- Necessary to design for extra torsion
- Additional eccentricity of 3% used for torsion

$$A_x = \left(\frac{\delta_{MAX}}{1.2\delta_{AVG}}\right)^2$$

Torsional Amplification Factor				
Loading	δ_A	δ_B	δ_{MAX}	A
Seismic X	0.5582	0.3474	-	1.534
Seismic XXY (5% Ecc)	-	-	0.67293	
Seismic XXY (7.67% Ecc)	-	-	0.6822	1.576
Seismic XXY (7.9% Ecc)	-	-	0.6836	1.583
Seismic Y	0.8155	0.5587	-	1.004
Seismic YX	-	-	0.8262	

Structural Redesign – Lateral System

Torsional Amplification

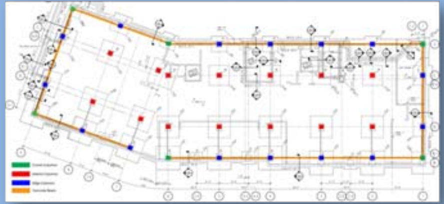
- Additional torsional considerations because of building's difference in center of mass and rigidity
- Necessary to design for extra torsion
- Additional eccentricity of 3% used for torsion

As a result of accidental torsion and the desire to investigate, additional lateral systems, exterior moment frames were designed.

Structural Redesign – Lateral System

ETABS Analysis

- Added because of torsion and mode period considerations
- End offset length = 12" for all beams
- Torsional amplification factor reduced to 1.
- Rigid zone factor = 0.5
- I_3 = 0.35 (ACI 10.10.4.1)
- Controlling Load Case = 1.2D + 1.6W + 1.0L + 0.5S



Structural Redesign – Lateral System

ETABS Analysis

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- I_3 = 0.35 (ACI 10.10.4.1)
- Controlling Load Case = 1.2D + 1.6W + 1.0L + 0.5S

Fundamental Period Comparison			
Mode Shape	Shear Wall Only Design	Shear Wall and Moment Frame Design	Difference
1 (Rotation)	T = 1.752 secs	T = 1.43 secs	0.322
2 (Y-Direction)	T = 1.40 secs	T = 1.312 secs	0.088
3 (X-Direction)	T = 0.963 secs	T = 0.914 secs	0.049
4 (Rotation)	T = 0.383 secs	T = 0.360 secs	0.023

Structural Redesign – Lateral System

Concrete Moment Frame - Columns

- Designed as intermediate moment frame as stated in ACI 21.3
- Redesign of all exterior and corner columns
- Loads determined using ETABS and takedowns
- Load Case (long direction) = 1.2D + 1.0E + 1.0L + 0.2S
- Load Case (short direction) = 1.2D + 1.6W + 1.0L + 0.5S

Concrete Column Loading (kips)								
Type	Area	Self Wt.	Dead	Live	Quake	Wind	Snow	LC
Corner (C55)	118.75	49.027	194.750	53.438	9.320	42.520	2.731	415.37
Exterior 1 (C65)	314.71	49.027	516.124	141.620	20.280	20.200	7.238	855.74
Exterior 2 (C80)	240.33	49.027	394.141	108.149	14.600	13.020	5.528	663.55

Structural Redesign – Lateral System

Concrete Moment Frame – Columns

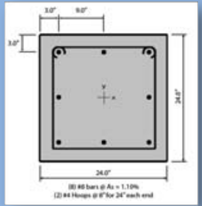
- Reinforcement designed using PCAColumn and hand calculations
- Special reinforcement per ACI 21.3
- Hoops required for 24" at each end
- Ties required throughout remainder of column

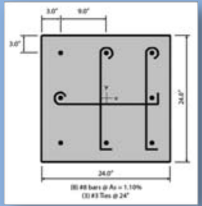
Type	Flexural Reinf.	Shear Reinf.		Transverse Reinf.
		Av_{min}	0.240	
Corner (C55)	(8) #8 @ 9"	Use (2) #4 Hoops @ 8" for 24" each end		Use (3) #3 Ties @ 24"
Exterior 1 (C65)	(8) #8 @ 9"	Use (2) #4 Hoops @ 8" for 24" each end		Use (3) #3 Ties @ 24"
Exterior 2 (C80)	(8) #8 @ 9"	Use (2) #4 Hoops @ 8" for 24" each end		Use (3) #3 Ties @ 24"

Structural Redesign – Lateral System

Concrete Moment Frame – Columns

- Reinforcement designed using PCAColumn and hand calculations
- Special reinforcement per ACI 21.3
- Hoops required for 24” at each end
- Ties required throughout remainder of column





Concrete Moment Frame – Beams

- Beams used both in gravity and lateral systems
- Initial beam cross section of 12" x 18"
- All reinforcement designed using ACI 21.3
- f'_c = 4000 psi & f_y = 60000 ksi

Given:	
M_u	40.48
V_u	5.3
T_u	0.26
b	12
h	18

Fifth Floor Loading

Fifth Floor B9

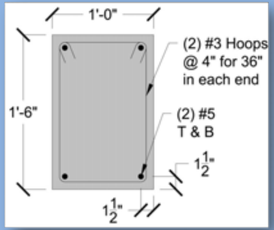
Estimation of d	
$bd^2 \geq 20M_u$	8.214
Use d =	15.5
A_s (Flexure)	
A_s	0.882
Use (2) #5 Bars T & B	

Torsional Reinforcement	
$T_u \leq ¼\phi 4\sqrt{f'_c}(A_c^2/P_c)$	36.885
Reinf. Needed?	no
Transverse Shear Reinf.	
V_c	23.527
$V_u \geq ½\phi V_c$	no

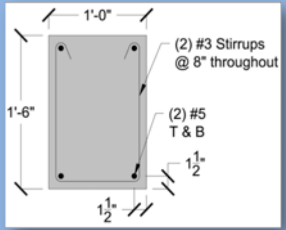
Shear Reinforcement			
$V_s \leq 4\sqrt{f'_c}bd$	yes		
S_{max} = d/4 = 3.875", use 4"		S_{max} = d/2 = 7.75", use 8"	
Av_{min}	0.120	Av_{min}	0.120
Use (2) #3 Hoops @ 4" for 36" @ each end		**Use (2) #3 Stirrups @ 8" throughout length**	

Structural Redesign – Lateral System

Concrete Moment Frame – Beams Details



End Beam Detail



Throughout Beam Detail

Structural Redesign – Lateral System

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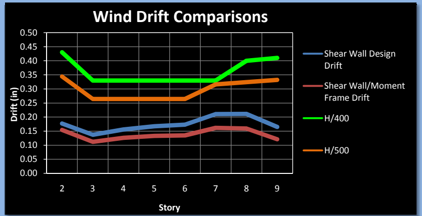
Drift Analysis

- Comparison between drift of shear wall only design and shear wall with concrete moment frames design
- Seismic (ASCE 7-05)
  - $\Delta = 0.020h_{sx}$
  - Amplified drift = $\delta_{xe}\ C_d/I$
- Wind
  - H/400 for story drift
  - H/500 for non-structural considerations



Structural Redesign – Lateral System

Drift Analysis

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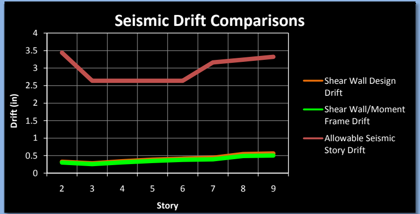
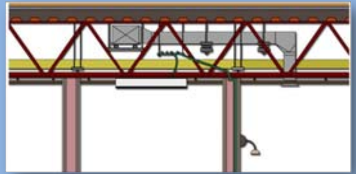
- Seismic (ASCE 7-05)
  - $\Delta = 0.020h_{sx}$
  - Amplified drift = $\delta_{xe}\ C_d/I$
- Wind
  - H/400 for story drift
  - H/500 for non-structural considerations

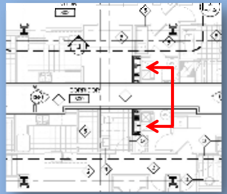


Architectural Detailing Study

Architectural Detailing

- Changes in the ceiling cavity caused by the change in structural system
- Existing system used as architectural feature to efficiently integrate mechanical systems into ceiling cavity
- New system utilizes 18” airspace to run all mechanical equipment





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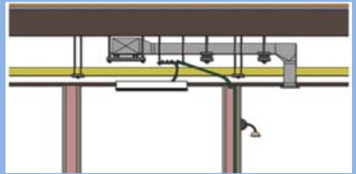
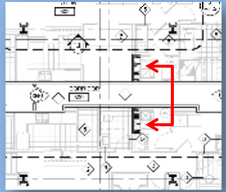
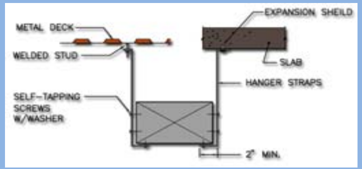




Architectural Detailing Study

Architectural Detailing

- Changes and differences in connections used for steel and concrete systems
- New connection uses concrete screws along with a lag screw expansion shield and anchor



Acoustics Breadth Study

Acoustics

- Owner expressed concern about building acoustics
- Investigated sound transmission through floor and wall assemblies
- Identified spaces with high expected noise level and studied their impact on the apartments
- Goal was to improve TL and STC values for assemblies

Acoustics Breadth Study

Floor Sound Isolation Assembly used on Floors 3 thru 8							
	125	250	500	1000	2000	4000	STC
Expected Noise Level in Apartments	62	64	67	70	68	63	
Minus expected background noise in Apartment (RC-30)	45	40	35	30	25	20	
Required NR	**17**	**24**	**32**	**40**	**43**	**43**	**50**
Minus 10 log a2/S	-1	-1	-1	-1	-1	-1	
Required TL	**18**	**25**	**33**	**41**	**44**	**44**	**50**
Finding an Adequate Wall Construction:							
3/4" Wood Flooring on 1" glass fiber	0	1	0	1	1	1	-
10" Reinforced Concrete Slab	44	48	55	58	63	67	-
18" Airspace	12	12	14	15	16	8	-
1/2" Gypsum Wall Board Finished Ceiling	15	20	25	29	32	27	-
Total TL of Wall Construction	**71**	**81**	**94**	**103**	**112**	**103**	**95**
Difference between Actual and Required Transmission Loss	53	56	61	62	68	59	45

Acoustics Breadth Study

Wall Sound Isolation Assembly to be used Between Apartments							
	125	**250**	**500**	**1000**	**2000**	**4000**	**STC**
Likely noise level in Apartments	62	64	67	70	68	63	
Minus expected background noise in Apartment (RC-30)	45	40	35	30	25	20	
Required NR	**17**	**24**	**32**	**40**	**43**	**43**	**50**
Minus 10 log a2/S	-1	-1	-1	-1	-1	-1	
Required TL	**18**	**25**	**33**	**41**	**44**	**44**	**50**
Finding an Adequate Wall Construction:							
2 Layers of 1/2" Gypsum Wall Board (each side)	19	26	30	32	29	37	-
2 Layers of 3 5/8" Steel Studs @ 24" O.C.	2	4	5	6	7	6	-
1/2" Air Gap	1	1	0	2	3	1	-
2 Layers of 3 1/2" fiberglass insulation	10	18	22	18	10	22	-
Total TL of Wall Construction	**32**	**49**	**57**	**58**	**49**	**66**	**61**
Difference between Actual and Required Transmission Loss	14	24	24	17	5	22	11

Acoustics Breadth Study

Acoustic Performance Comparison				
Assembly	STC - HUD Noise Control Guide	STC - Existing Design	STC - New Design	Difference
Floor Assembly between 1st Floor Retail and 2nd Floor Apartment	STC - 56	STC - 62	STC - 95	+33
Floor Assembly between Floors on Apartment Levels 3 thru 8	STC - 56	STC - 58	STC - 95	+37
Floor Assembly between Penthouse Apartment and Rooftop Mechanical Equipment	STC - 56	STC - 62	STC - 105	+43
Wall Assembly between Elevator Shaft and Apartments	STC - 56	STC - 55	STC - 75	+20
Wall Assembly between two Apartments and an Apartment and a Corridor	STC - 56	STC - 57	STC - 61	+4

Conclusions and Recommendations

Conclusions and Recommendations

- **Redesign of structural system caused the following:**
  - Reduced building motion in terms of building period and drift
  - Possible overdesign with the inclusion of concrete moment frames
  - Minor impacts on architectural aspects of the building
  - Better acoustical performance of all floor/wall assemblies
- **Recommendations**
  - Existing structural system is most likely the most efficient
  - Benefits of the use of reinforced concrete in the design of mid-rise apartment buildings is evident

Overall, the main objective of learning how to analyze and design all aspects of a concrete structure was accomplished!

Acknowledgements

Zamagias Properties
Michael Heins

WBCM, LLC
Brian Channer, PE
Mike Wuerthele, PE, Senior VP
Brandon Pettner
Jeremy Urban

Indovina Associates Architects
Brian Roth, AIA

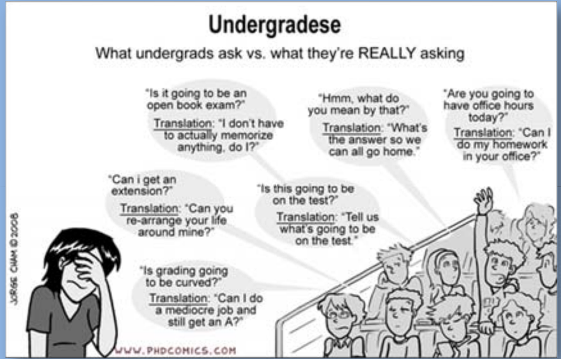
CJL Engineering
Gary Czyrnik
Harry Hoover

The Penn State University
Prof. M.K. Parfitt
Dr. Linda M. Hanagan
Prof. Robert J. Holland
Dr. Ali Memari

AE Students
Scott Rabold & the Bat Cave

Lastly, I would like to thank all of my peers in the AE program, along with my family and friends for their endless support and encouragement through this entire project. Your help was invaluable and for that I am extremely grateful.

Questions?



Undergradese
What undergrads ask vs. what they're REALLY asking
"Is it going to be an open book exam?" Translation: "I don't have to actually memorize anything, do I?"
"Hmm, what do you mean by that?" Translation: "What's the answer so we can all go home."
"Are you going to have office hours today?" Translation: "Can I do my homework in your office?"
"Can i get an extension?" Translation: "Can you re-arrange your life around mine?"
"Is this going to be on the test?" Translation: "Tell us what's going to be on the test."
"Is grading going to be curved?" Translation: "Can I do a mediocre job and still get an A?"
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1. Explain Newton's First Law of Motion in your own words.
!
Yakka Foob Mog. Grug Pubbawup Zink Wattoom Gazork. Chumble Spuzz.
I LOVE LOOPHOLES.