Inova Fairfax Hospital

South Patient Tower

Falls Church, VA

Senior Thesis 2012

Faculty Advisor: Dr. Richard Behr

Nathan McGraw | Structural Option

South Patient Tower

- Building Introduction
- Existing Structural System
- Problem Statement
- Proposed Solution
- Gravity Redesign
- Fixed Base System
- Base Isolation System
- Comparison of Designs
- Construction Management Breadth
- Questions/Comments

Building Introduction

- Hospital/Patient Tower
- Located in Falls Church, VA
- 236,000 SF
- Height – 145' to Main Roof Level
- Construction Cost - $76 Million
- Summer 2010 – Fall 2012
- LEED Silver Certification
- Design – Bid – Build

Site Map

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Project Team

- **Owner:** Inova Fairfax Hospital
- **General Contractor:** Turner Construction
- **Architect/Planner:** Wilmot/Sanz Architects
- **Structural Engineer:** Cagley & Associates
- **MEP:** RMF Engineering, INC.
- **Civil Engineer:** Dewberry & Davis LLC

Introduction

South Patient Tower

Design Highlights

Introduction

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- **Addition to existing hospital (not depicted in picture)**
- **Designed to maintain floor-to-floor relationships**
- **Once completed, construction of the Women's Hospital will be undertaken**
- **Design Highlights:**
  - 174 all-intensive patient rooms
  - Medical/surgical beds situated on five floors
  - Three floors dedicated to ICU beds

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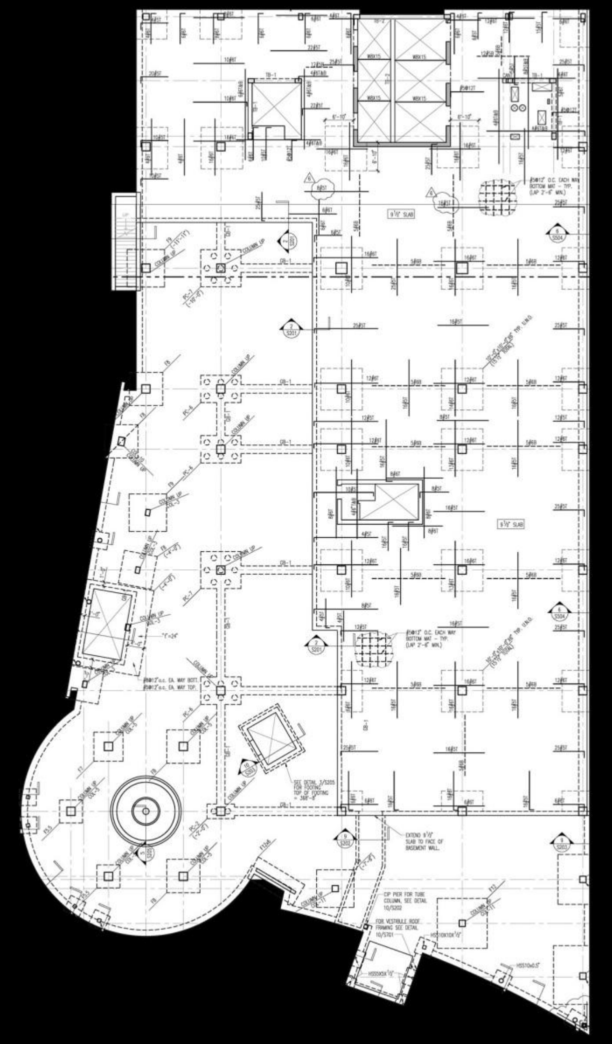
Existing Structural System

- Foundation
- Floor System
- Lateral System

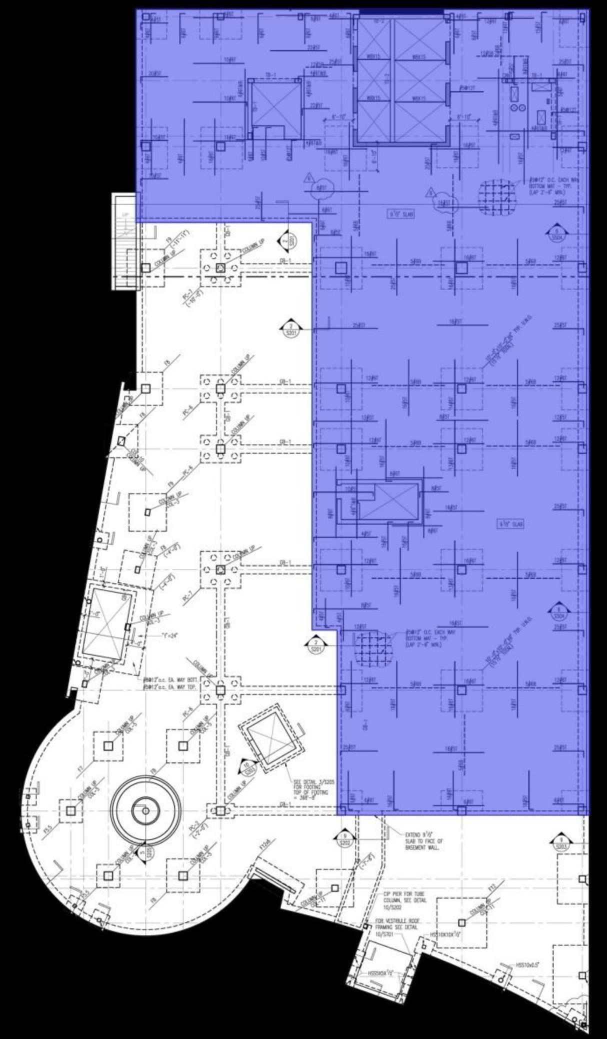
Foundation



Existing Structural System

Foundation

- Foundation
  - Net allowable bearing pressure of 3000 psf
  - Equivalent fluid pressure = 60 psf/ft
  - Friction factor of 0.30
  - 16 in. diameter auger-cast piles and pile caps
  - 5 in. slab on grade
- Floor System
- Lateral System



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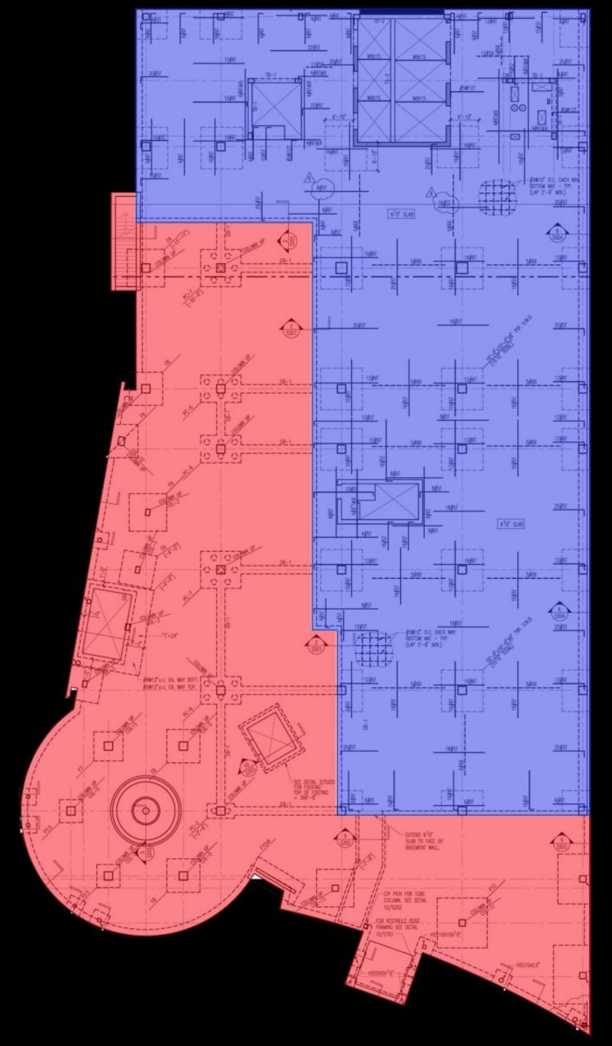

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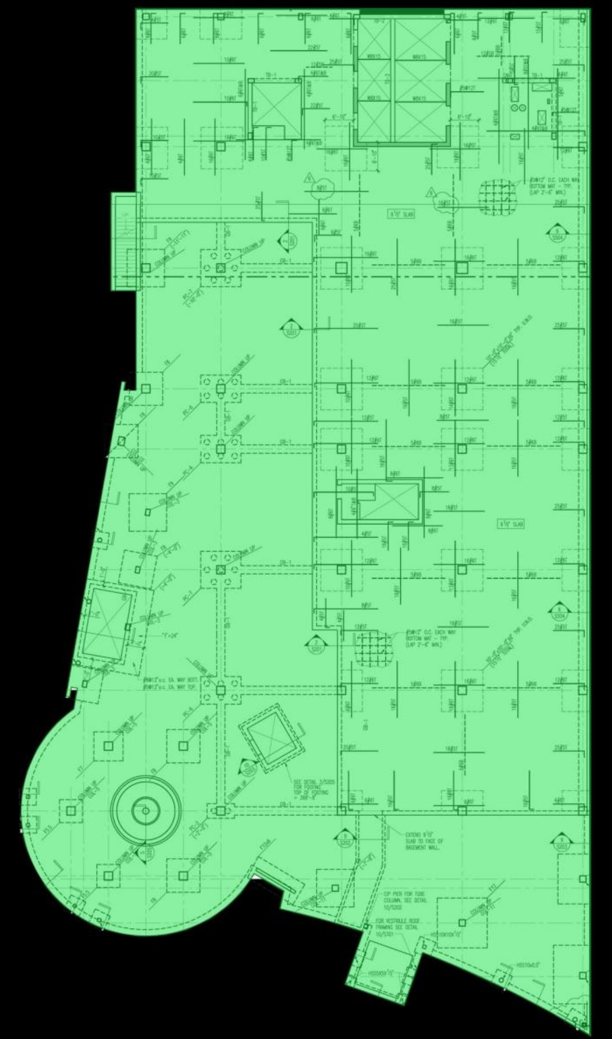
Existing Structural System

- Foundation
- **Floor System**
  - Typical bay size: 29 ft x 29 ft
  - 9.5 in. two-way flat slab concrete system with 15.5 in. drop panels
  - Typical column: 24 in. x 24 in.
- Lateral System

Floor Plans



Ground Floor

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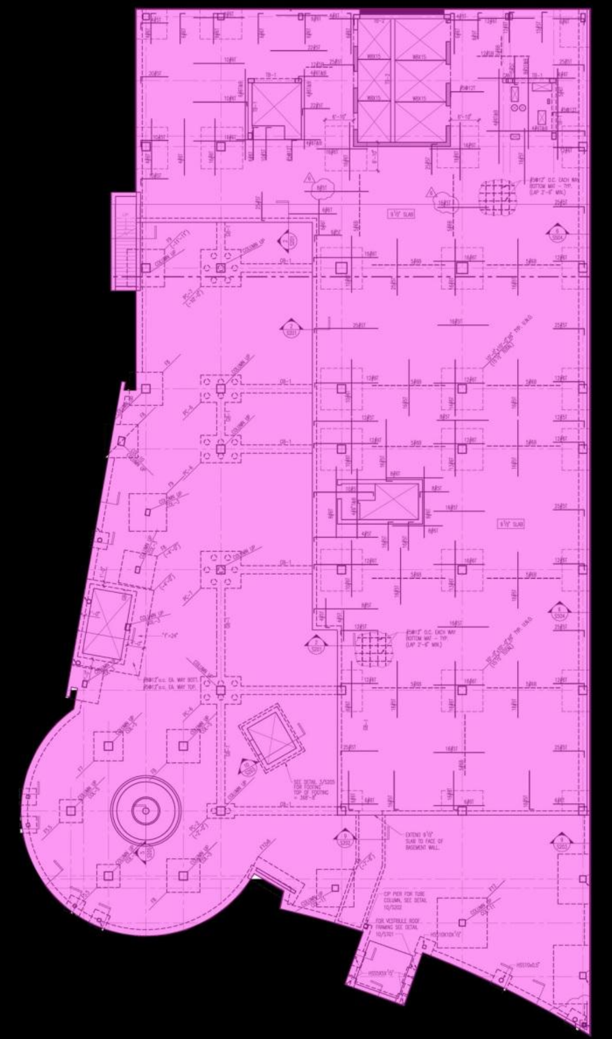

1st Floor

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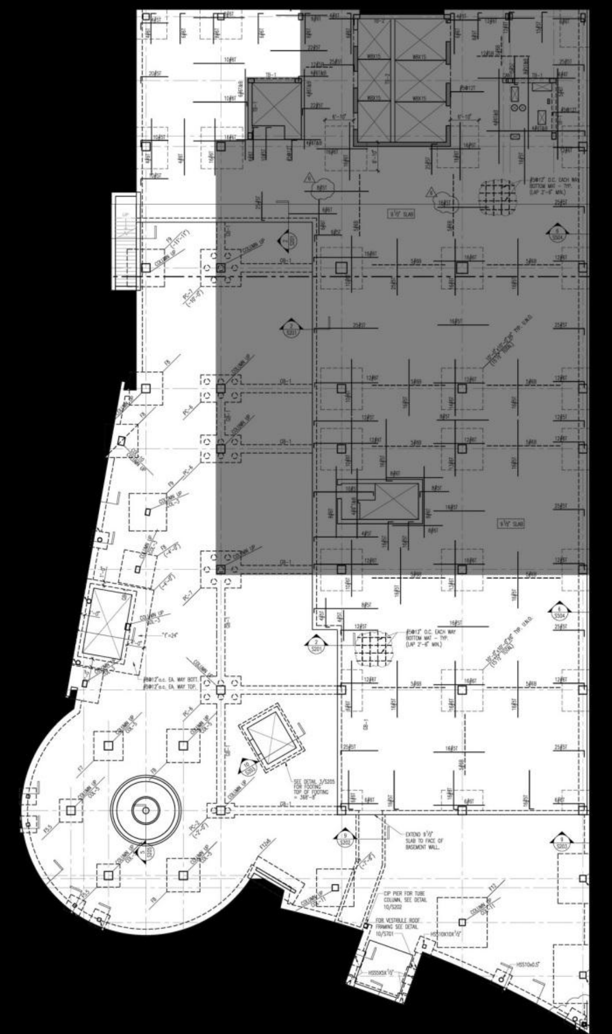

2nd Floor

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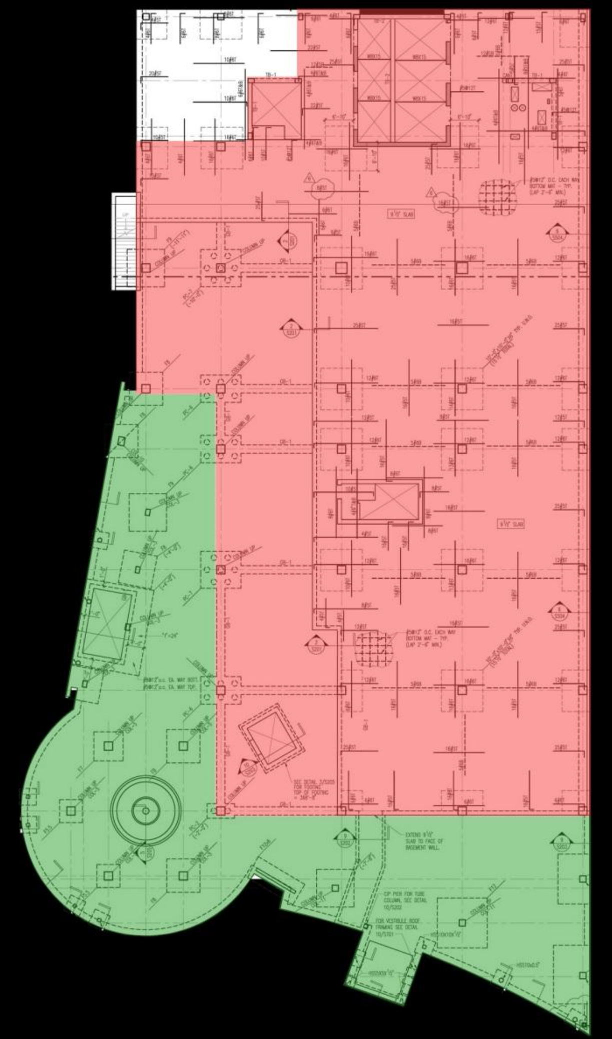

3rd Floor

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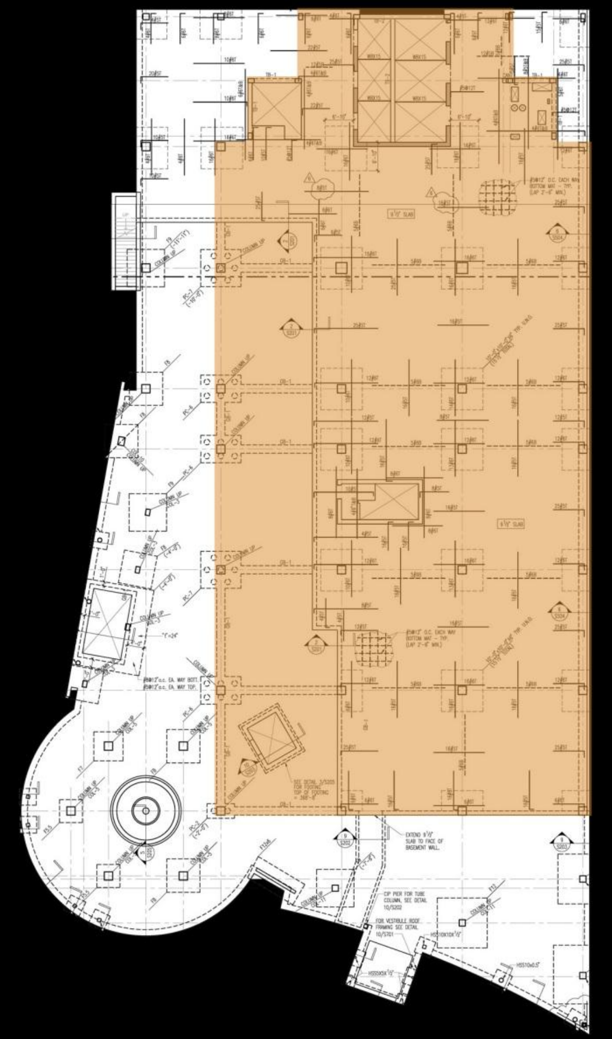

4th – 11th Floors

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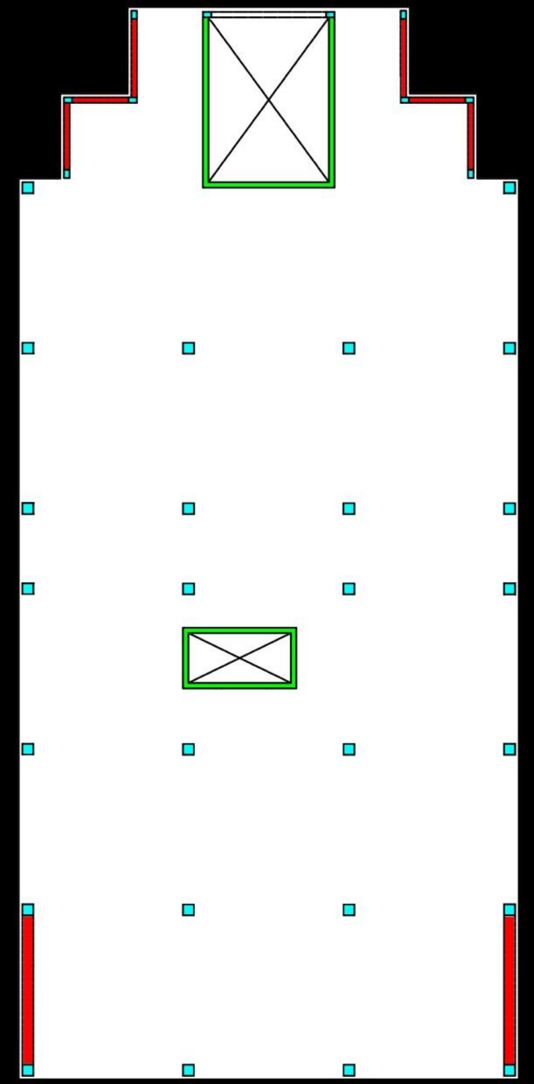
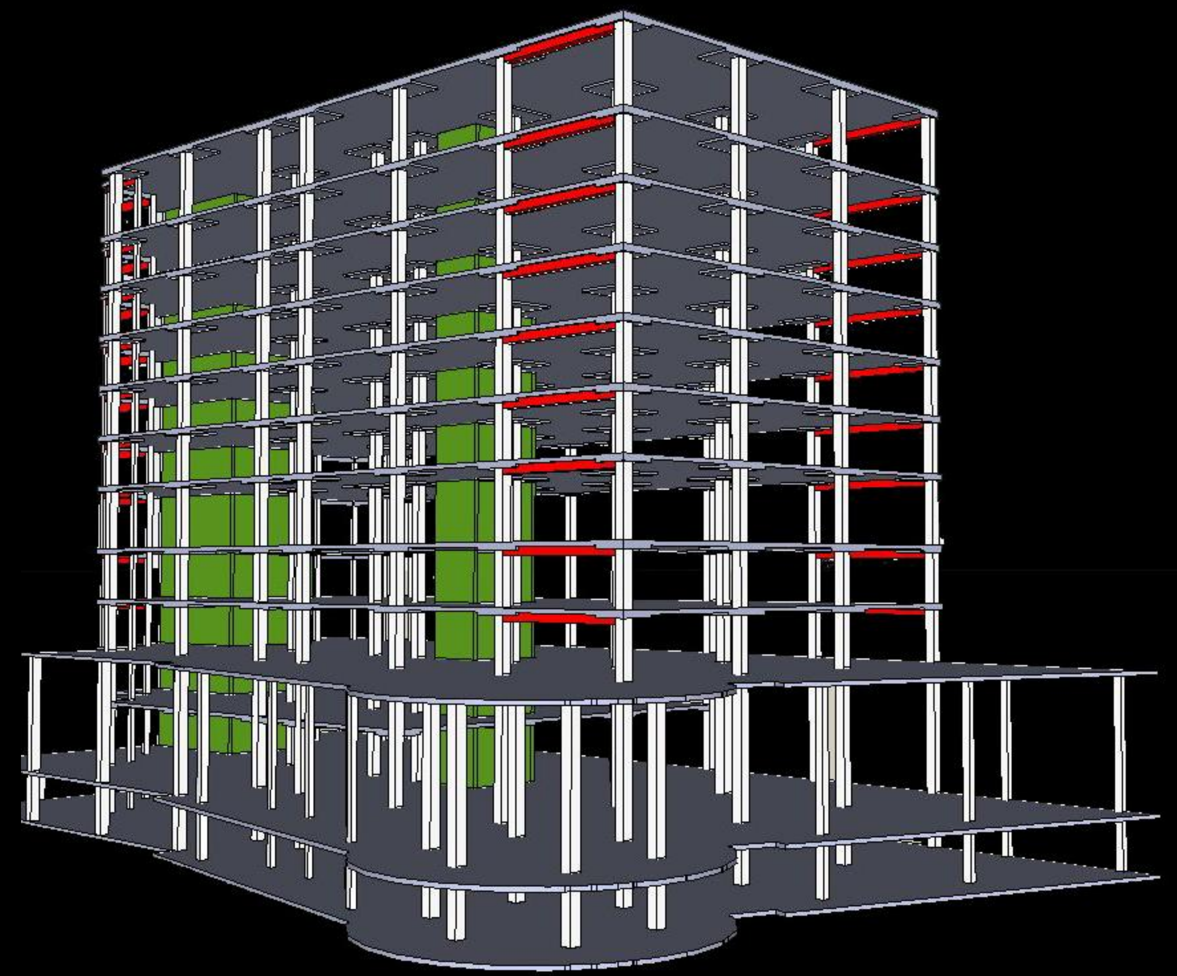
Existing Structural System

- Foundation
- Floor System
- Lateral System
  - 7 shear walls located around elevator/staircase cores
  - Scattered moment frames situated mainly in the Y-Direction

Lateral System





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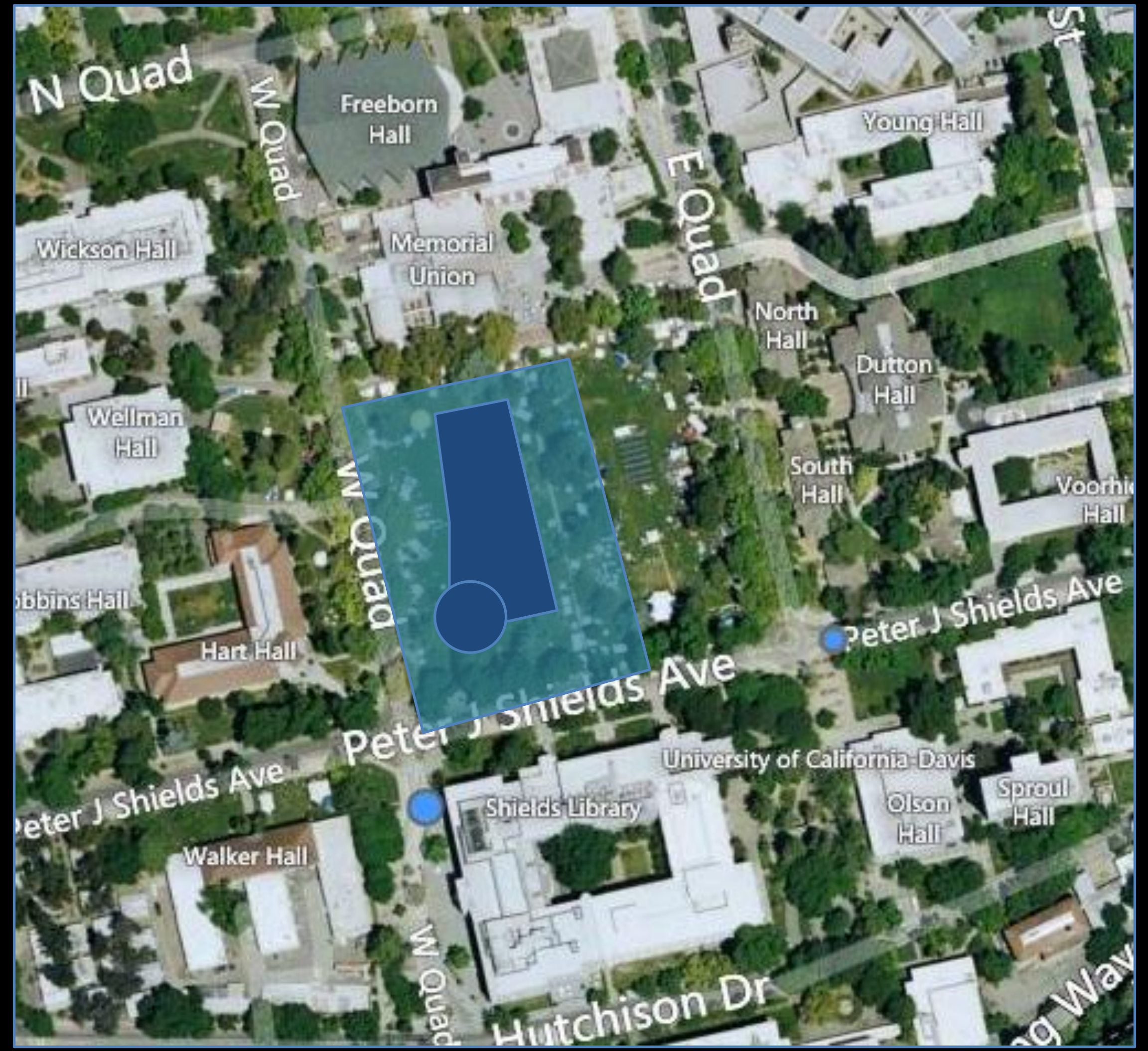
Problem Statement

- **Interest in seismic design**
- **New scenario created**
  - Building commissioned by the University of California – Davis (near Sacramento, CA)
- **“Hospital buildings that house patients who have less than the capacity of normally healthy persons to protect themselves…must be reasonably capable of providing services to the public after a disaster.”**

  - Alfred E. Alquist Hospital Facilities Seismic Safety Act of 1983

California Site



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Problem Solution

- **3 designs undertaken in concrete**
  - One-Way Slab Floor System in VA
    - Base Model
  - Immediate Occupancy Design in California
    - Traditional Fixed Base System (CA – Fixed Model)
  - Immediate Occupancy Design in California
    - Augmented with Base Isolators (CA – Base Isolation Model)

Goals

- **Comparison between the various designs includes:**
  - Existing Structure vs. CA – Fixed Model
  - Existing Structure vs. CA – Base Isolation Model
  - CA – Fixed Model vs. CA – Base Isolation Model (Traditional system vs. High Seismic Performance System)
- **Utilize MAE coursework to accomplish the above tasks**

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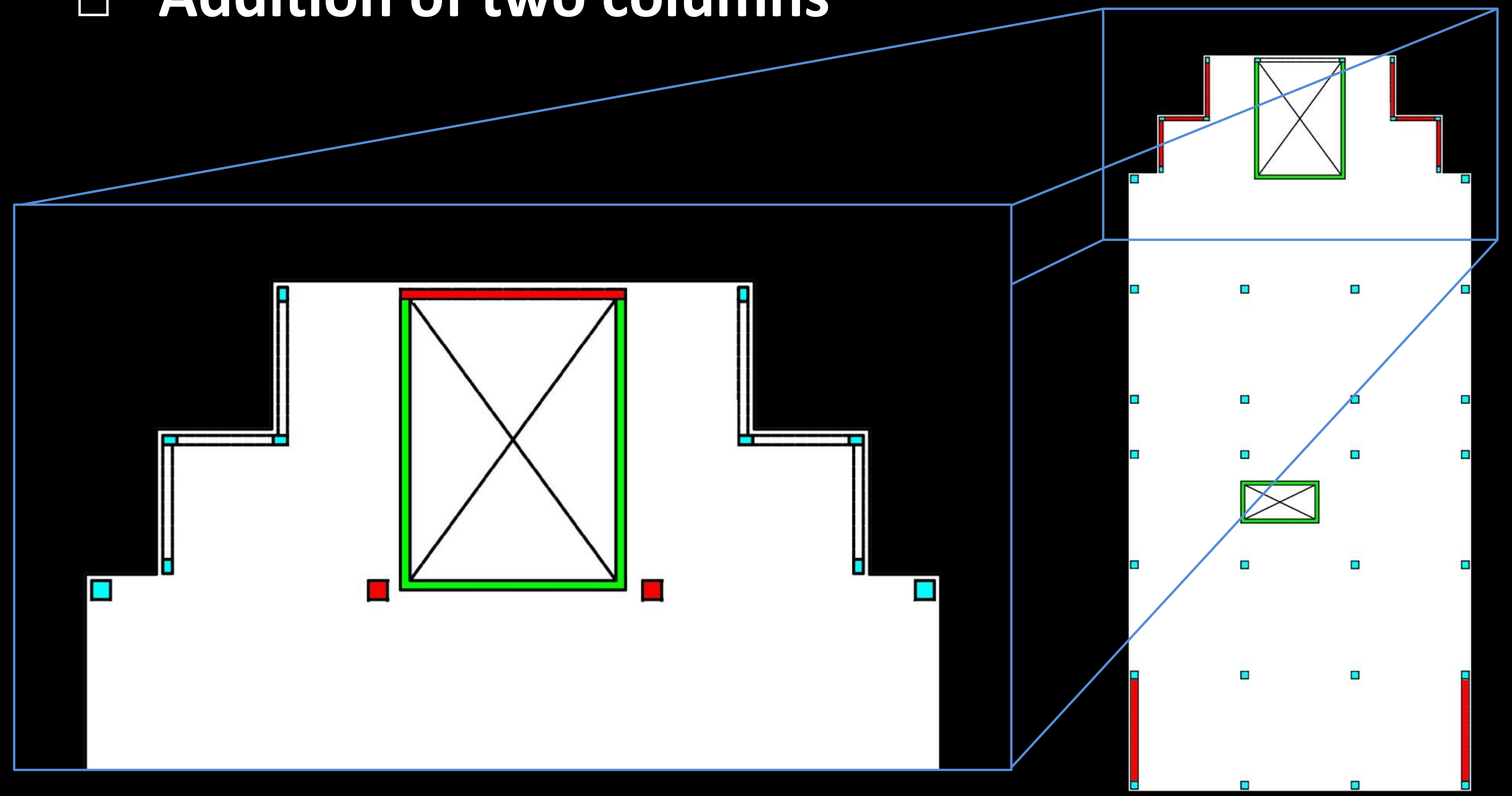
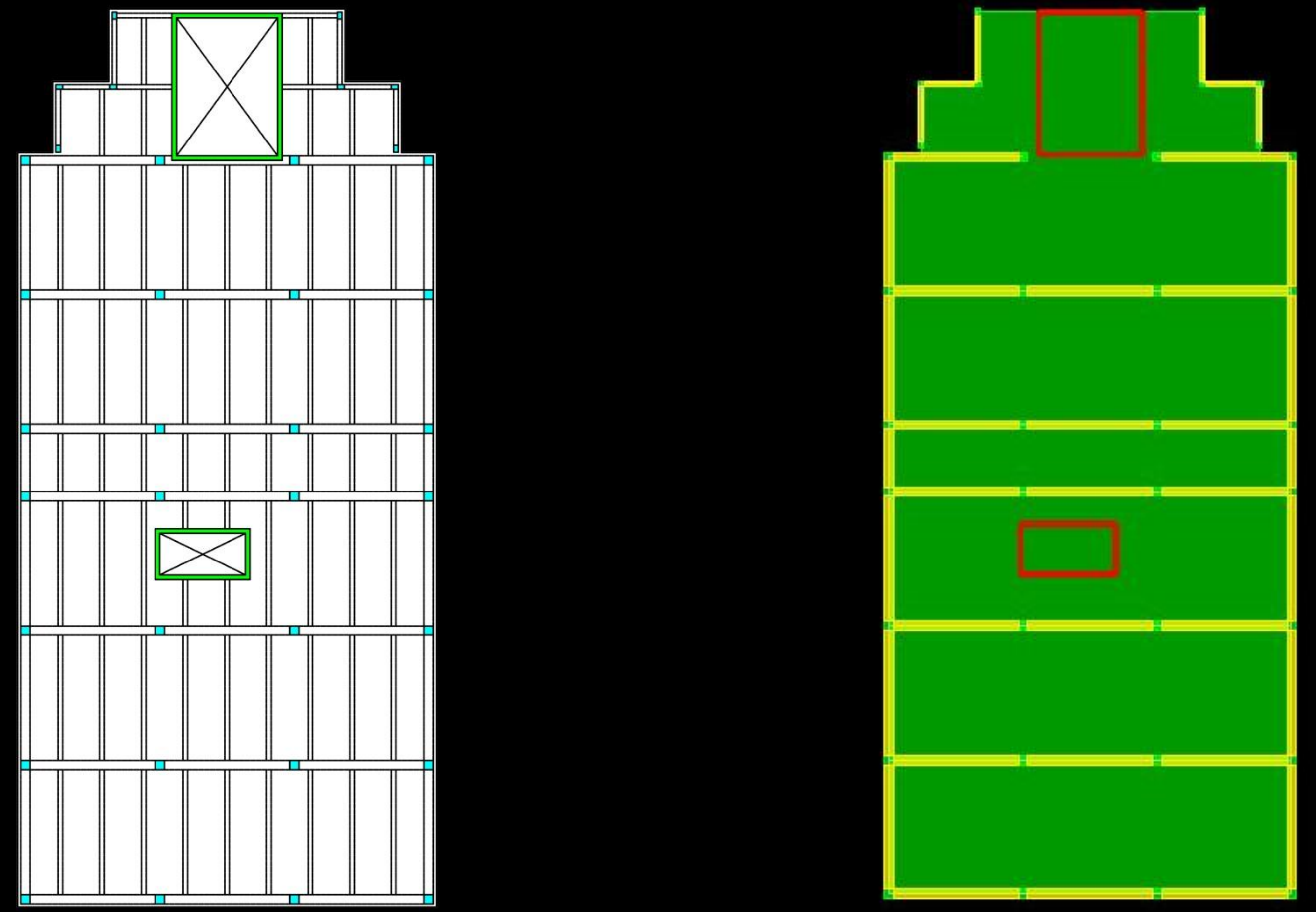
System Alterations

Proposed One-Way Layout

- Addition of shear wall in northern core
- Addition of two columns



- Moment frames situated along the existing column lines and in the X-Direction



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One-Way Slab Design

RAM Concept

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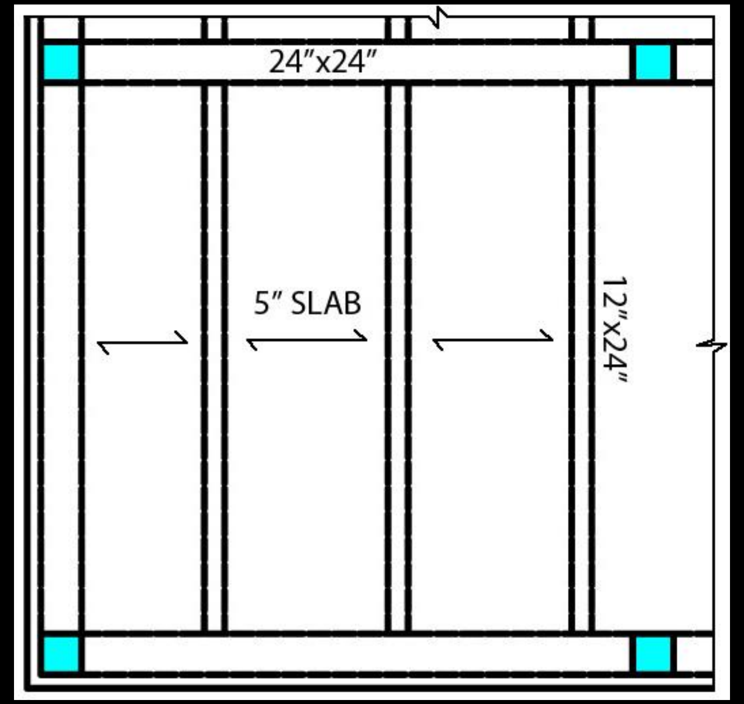
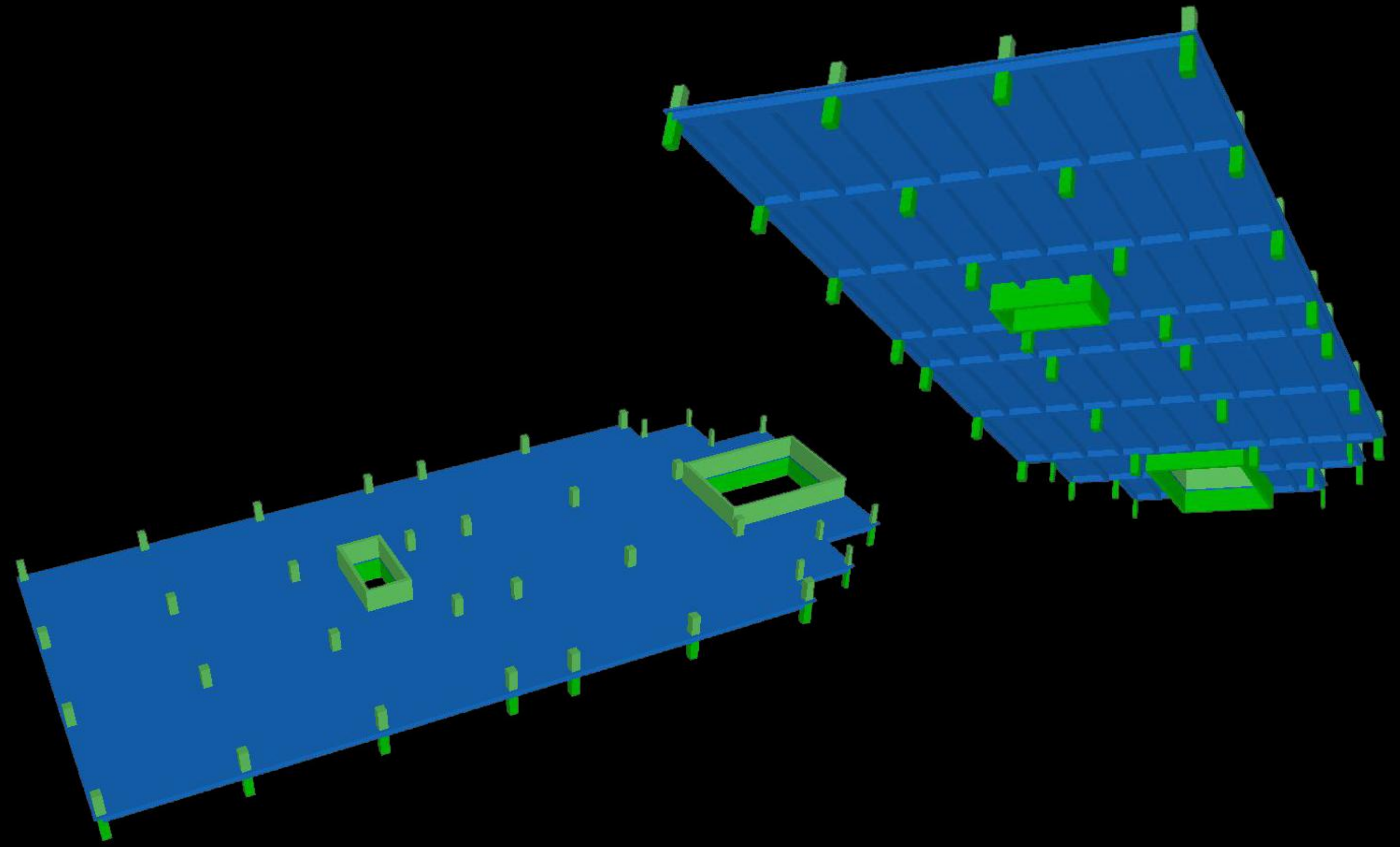


Designed One-Way Floor Slab System			
Member	Dimensions	Location	Reinfocement
Slab	5"	Top/Bottom	# 4 @ 12"
		Transverse	# 4 @ 18"
Joist	12"x24"	At Support (top)	(4) # 6's
		At Midspan (bottom)	(3) # 6's
		At Support (top)	(4) # 6's
Girder	24"x24"	At Support (top)	(5) # 9's
		At Midspan (bottom)	(4) # 8's
		At Support (top)	(5) # 9's



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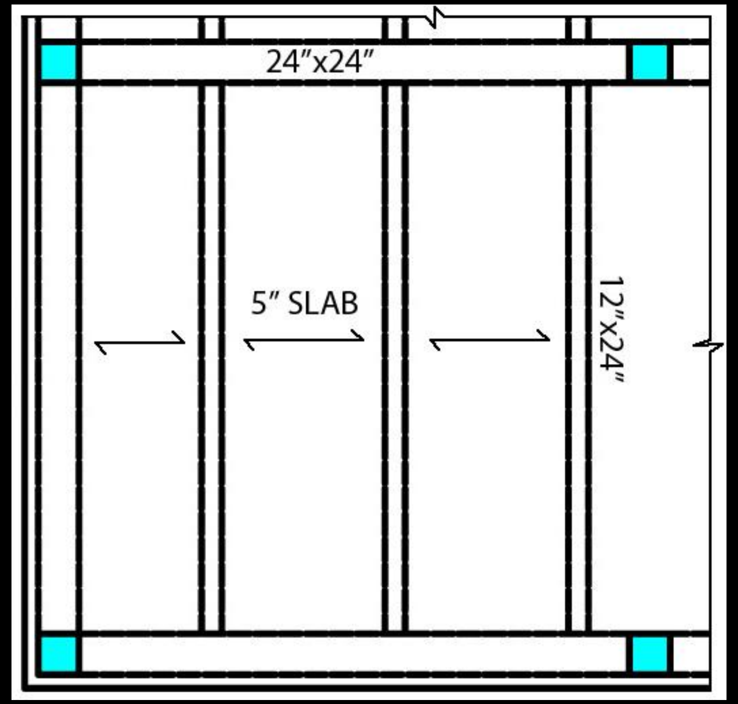

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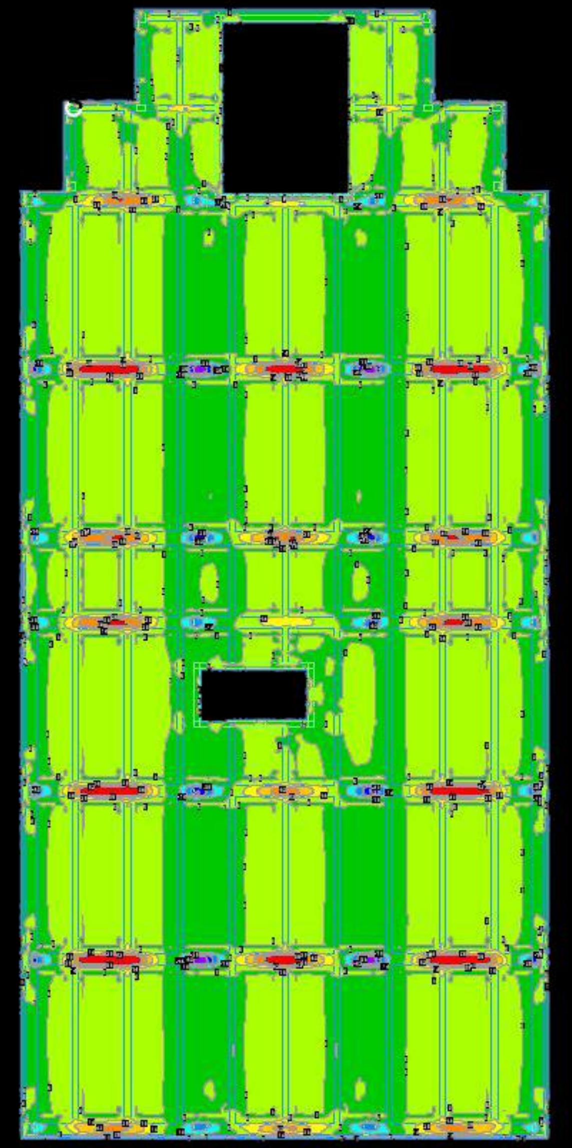

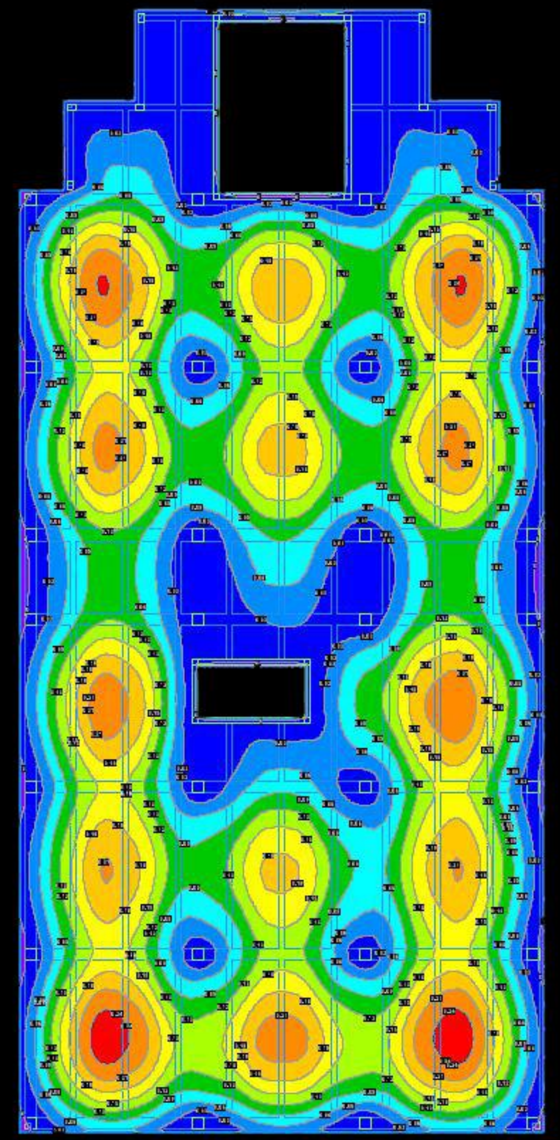

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Fixed Base System

ASCE 41-06

- **ASCE 41-06 – *Seismic Rehabilitation of Existing Buildings***
  - S-3: "Life Safety"
    - Concrete Frames – 2% Transient Drift
    - Concrete Walls – 1% Transient Drift
  - S-1: "Immediate Occupancy"
    - Concrete Frames – 1% Transient Drift
    - Concrete Walls – 0.5% Transient Drift

Table C1-3 Structural Performance Levels and Damage[1, 2, 3]—Vertical Elements (continued)

		Structural Performance Levels		
Elements	**Type**	**Collapse Prevention S-5**	**Life Safety S-3**	**Immediate Occupancy S-1**
Concrete Walls	Primary	Major flexural and shear cracks and voids. Sliding at joints. Extensive crushing and buckling of reinforcement. Failure around openings. Severe boundary element damage. Coupling beams shattered and virtually disintegrated.	Some boundary element stress, including limited buckling of reinforcement. Some sliding at joints. Damage around openings. Some crushing and flexural cracking. Coupling beams: extensive shear and flexural cracks; some crushing, but concrete generally remains in place.	Minor hairline cracking of walls, <1/16" wide. Coupling beams experience cracking <1/8" width.
	Secondary	Panels shattered and virtually disintegrated.	Major flexural and shear cracks. Sliding at joints. Extensive crushing. Failure around openings. Severe boundary element damage. Coupling beams shattered and virtually disintegrated.	Minor hairline cracking of walls. Some evidence of sliding at construction joints. Coupling beams experience cracks <1/8" width. Minor spalling.
	Drift	2% transient or permanent	1% transient; 0.5% permanent	0.5% transient; negligible permanent

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Fixed Base System

Lateral System Design

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- **ASCE 7-05: *Minimum Design Loads for Buildings and Other Structures***

$$1.4(D+F)$$
$$1.2(D+F+T)+1.6(L+H)+0.5(L_r \text{ or } S \text{ or } R)$$
$$1.2D+1.6(L_r \text{ or } S \text{ or } R)+(L \text{ or } 0.8W)$$
$$1.2D+1.6W+L+0.5(L_r \text{ or } S \text{ or } R)$$
$$1.2D+1.0E+L+0.2S$$
$$0.9D+1.6W+1.6H$$
$$0.9D+1.0E+1.6H$$

Base Shear Values			
	Direction	Existing Structure (VA)	CA - Fixed Model
Wind	N-S	391 k	322 k
	E-W	1028 k	666 k
Seismic	N-S	747 k	2026 k*
	E-W	747 k	2026 k*

*Modal Response Spectrum Analysis Performed (85% Controlled)
ELF = 2384 k

South Patient Tower

Fixed Base System

Lateral System Design

- ASCE 7-05: *Minimum Design Loads for Buildings and Other Structures*

$1.4(D + F)$

$1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R)$

$1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.8W)$

$1.2D + 1.6W + L + 0.5(L_r \text{ or } S \text{ or } R)$

$\mathbf{1.2D + 1.0E + L + 0.2S}$

$0.9D + 1.6W + 1.6H$

$0.9D + 1.0E + 1.6H$

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Fixed Base System

Lateral System Design

- **Response Modification Factor**
  - R = 6.5
  - $C_d = 5$
  - Dual systems with intermediate moment frames capable of resisting at least 25% of prescribed seismic forces
  - Special reinforced concrete shear walls
- **Torsional Irregularity**
  - Horizontal Irregularity:
    - Type 1a: 6th – Penthouse
    - Type 1b: 1st – 5th
    - Redundancy Factor = 1.3

	Model With Moment Frames						Deflection Criteria Met?			
12" Shear Walls	Frame Size	Period	Maximum Drift X (in.)	Maximum Drift Y (in.)	S-3 Δ_a (1.0%)	S-1 Δ_a (0.5%)	$S\text{-}3_X$	$S\text{-}3_Y$	$S\text{-}1_X$	$S\text{-}1_Y$
	24x24	1.944	1.650	1.316	1.84	0.92	Yes	Yes	No	No
	24x28	1.786	1.292	1.199	1.84	0.92	Yes	Yes	No	No
	24x32	1.651	1.038	1.093	1.84	0.92	Yes	Yes	No	No
	24x36	1.537	0.859	1.001	1.84	0.92	Yes	Yes	Yes	No

	Model With Moment Frames						Deflection Criteria Met?			
16" Shear Walls	Frame Size	Period	Maximum Drift X (in.)	Maximum Drift Y (in.)	S-3 Δ_a (1.0%)	S-1 Δ_a (0.5%)	$S\text{-}3_X$	$S\text{-}3_Y$	$S\text{-}1_X$	$S\text{-}1_Y$
	24x24	1.787	1.480	1.063	1.84	0.92	Yes	Yes	No	No
	24x28	1.660	1.201	0.986	1.84	0.92	Yes	Yes	No	No
	24x32	1.548	0.992	0.915	1.84	0.92	Yes	Yes	No	Yes
	24x36	1.450	0.836	0.851	1.84	0.92	Yes	Yes	Yes	Yes

	Model With Moment Frames						Deflection Criteria Met?			
24" Shear Walls	Frame Size	Period	Maximum Drift X (in.)	Maximum Drift Y (in.)	S-3 Δ_a (1.0%)	S-1 Δ_a (0.5%)	$S\text{-}3_X$	$S\text{-}3_Y$	$S\text{-}1_X$	$S\text{-}1_Y$
	24x24	1.564	1.210	0.767	1.84	0.92	Yes	Yes	No	Yes
	24x28	1.475	1.028	0.727	1.84	0.92	Yes	Yes	No	Yes
	24x32	1.393	0.882	0.688	1.84	0.92	Yes	Yes	Yes	Yes
	24x36	1.319	0.766	0.652	1.84	0.92	Yes	Yes	Yes	Yes

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Base Isolation System

- Three basic elements in any particular seismic isolation system:

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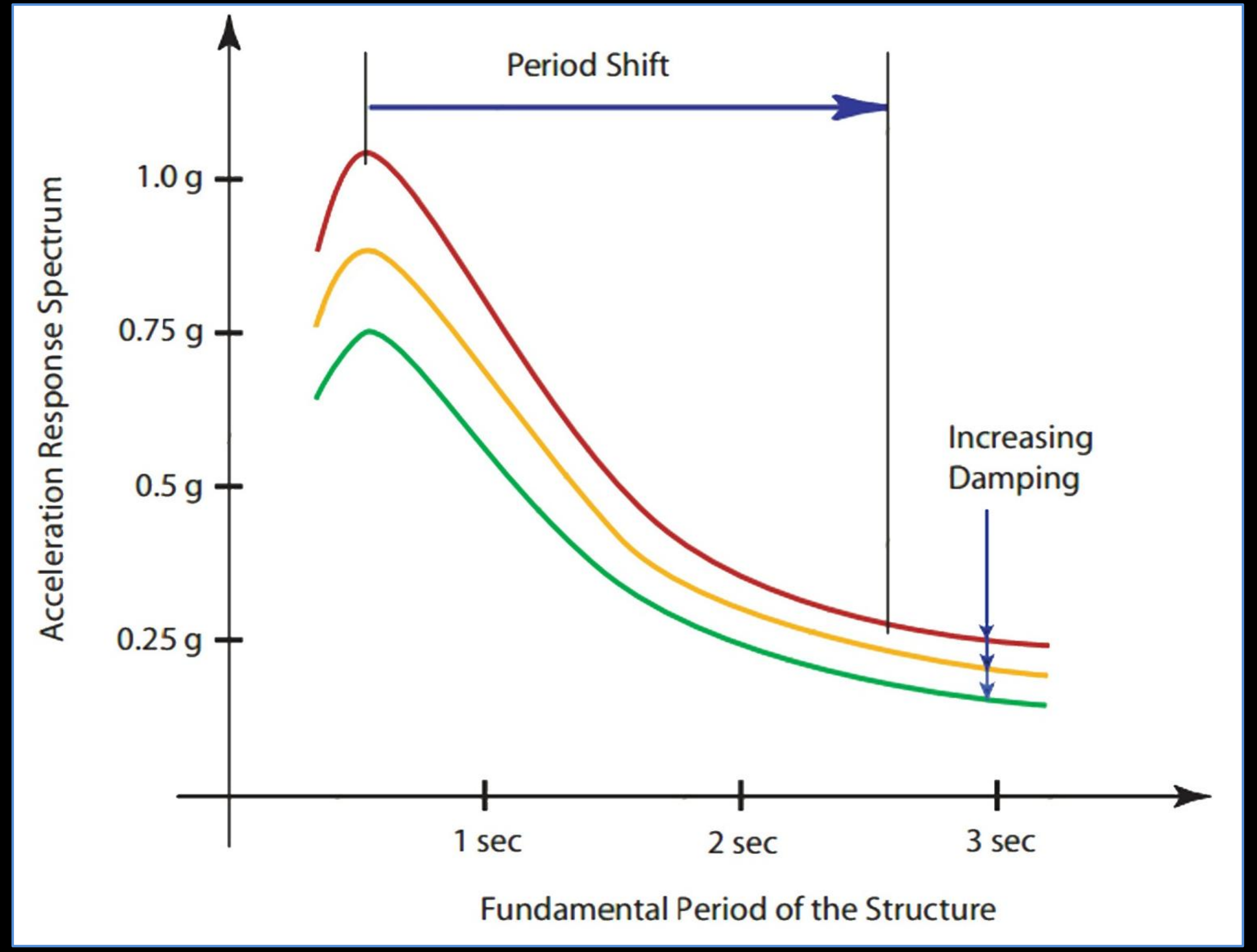
- **Three basic elements in any particular seismic isolation system:**
  - Flexible mounting system so that the period of vibration of the total system is lengthened (reduces force response and acceleration for floor systems)

Basic Properties



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  - Damper or energy dissipater to decrease deflections and drift

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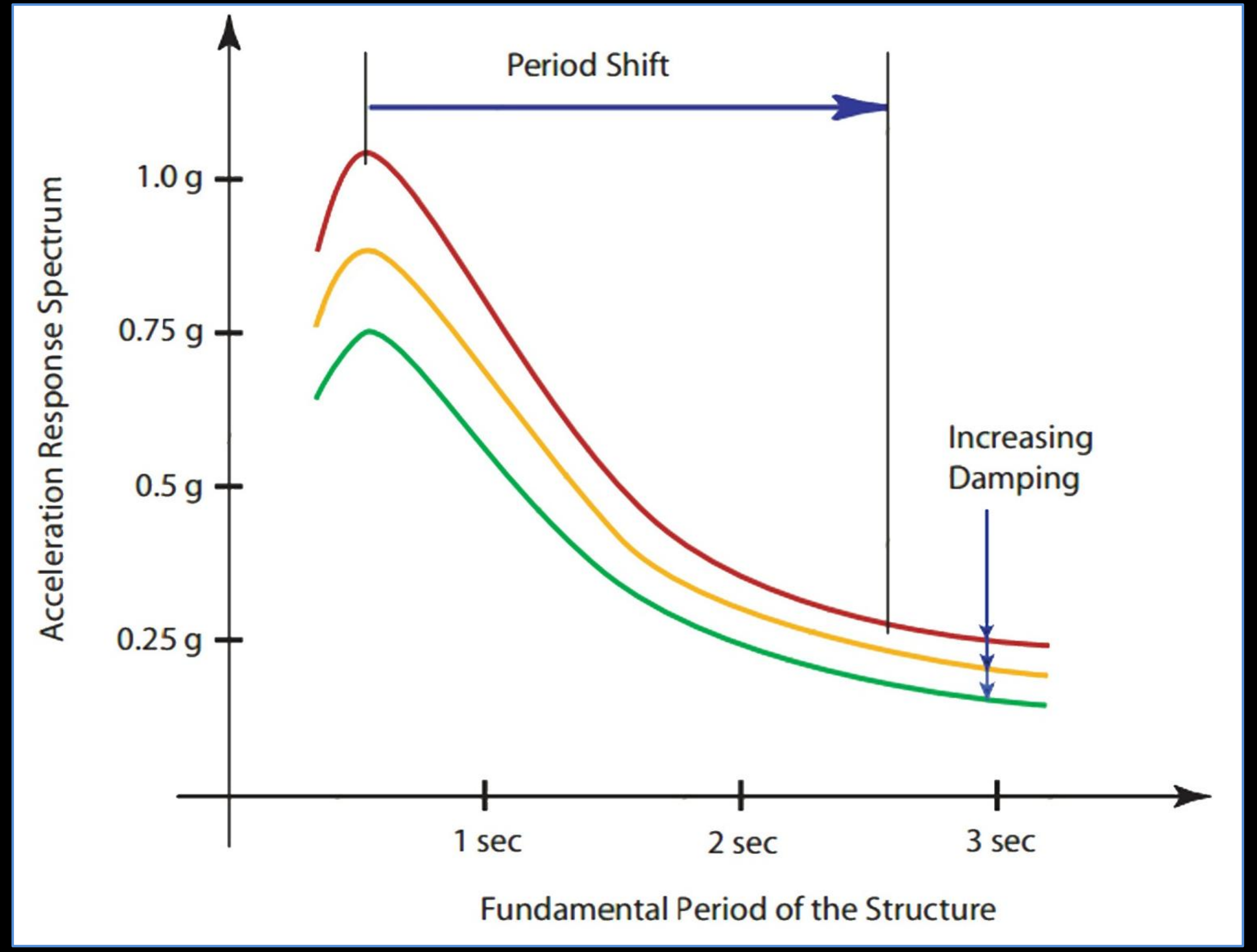

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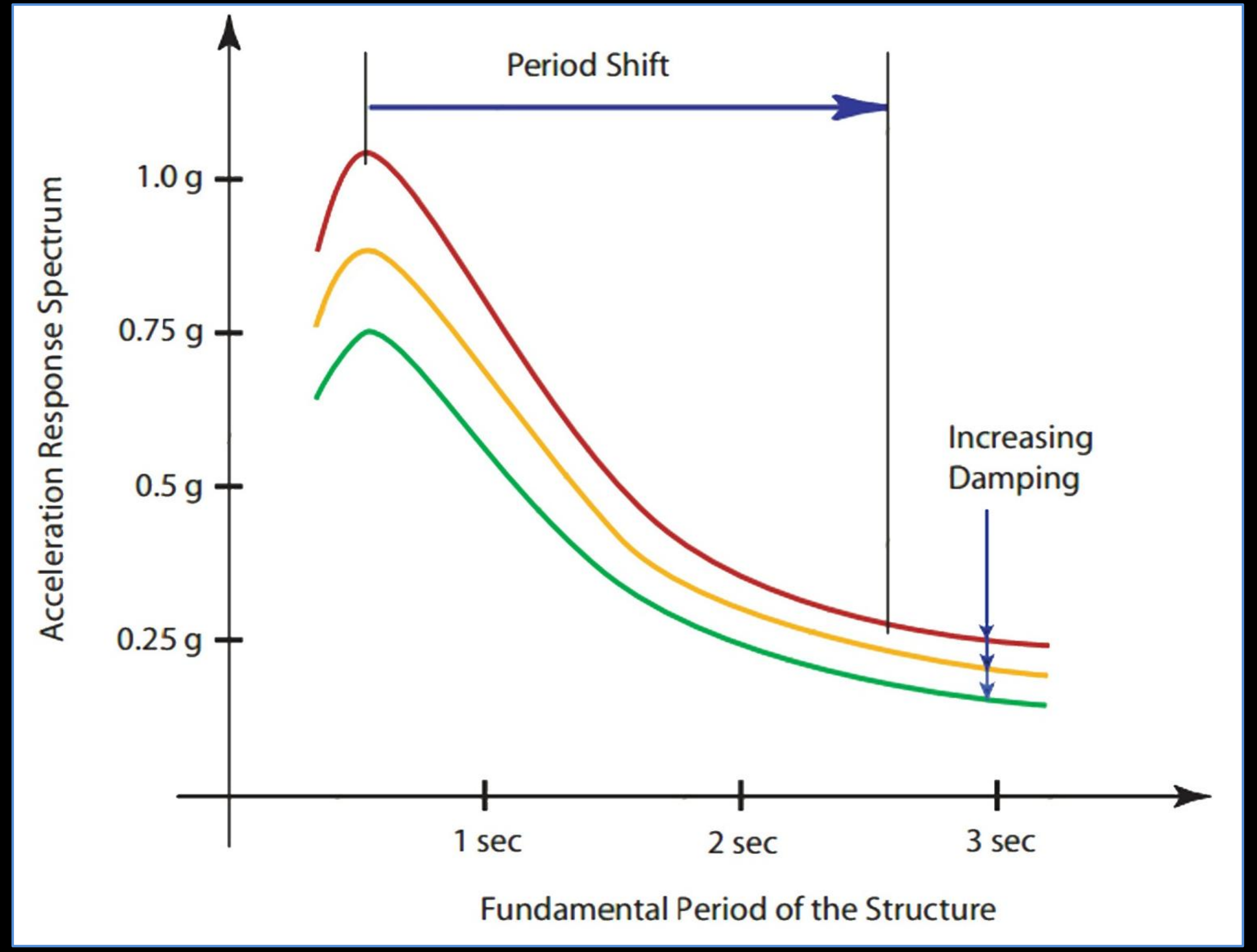
  - Flexible mounting system so that the period of vibration of the total system is lengthened (reduces force response and acceleration for floor systems)
  - Damper or energy dissipater to decrease deflections and drift
  - Means of controlling low load levels such as wind (secondary/backup system)

Basic Properties



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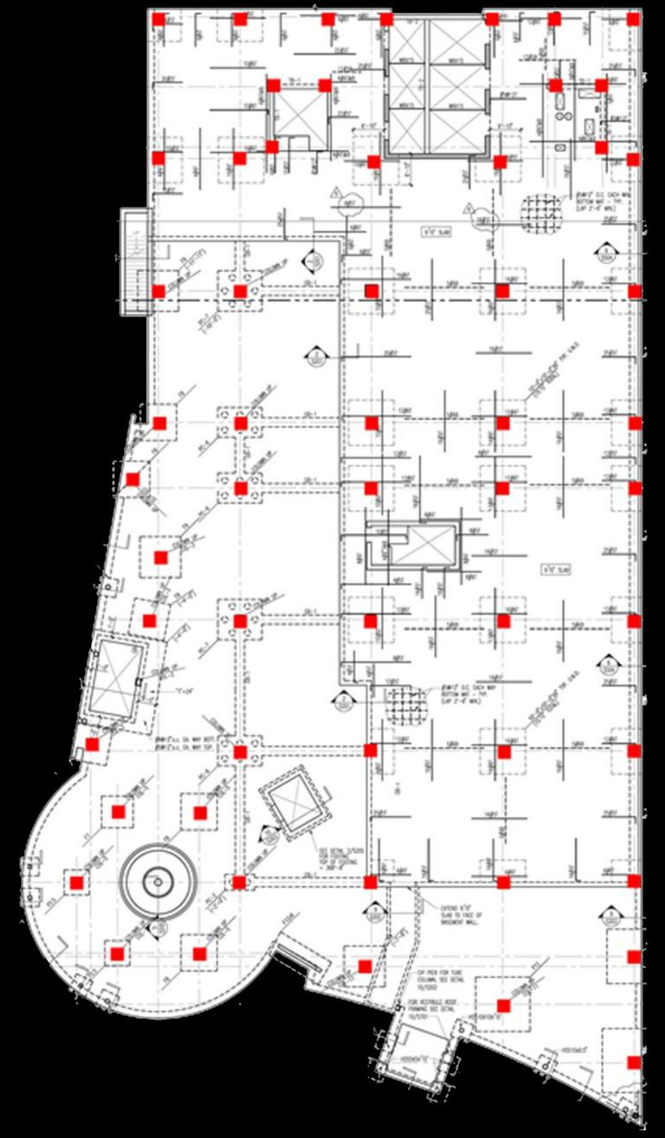
Base Isolation System

- **Base isolators generally attached near the foundation level**
  - Isolators placed directly beneath ground floor slab
    - Crawl space
      - Inspect/Maintenance
      - Repair damages
    - Distribution of forces
  - 60 isolators

Base Isolation Layout



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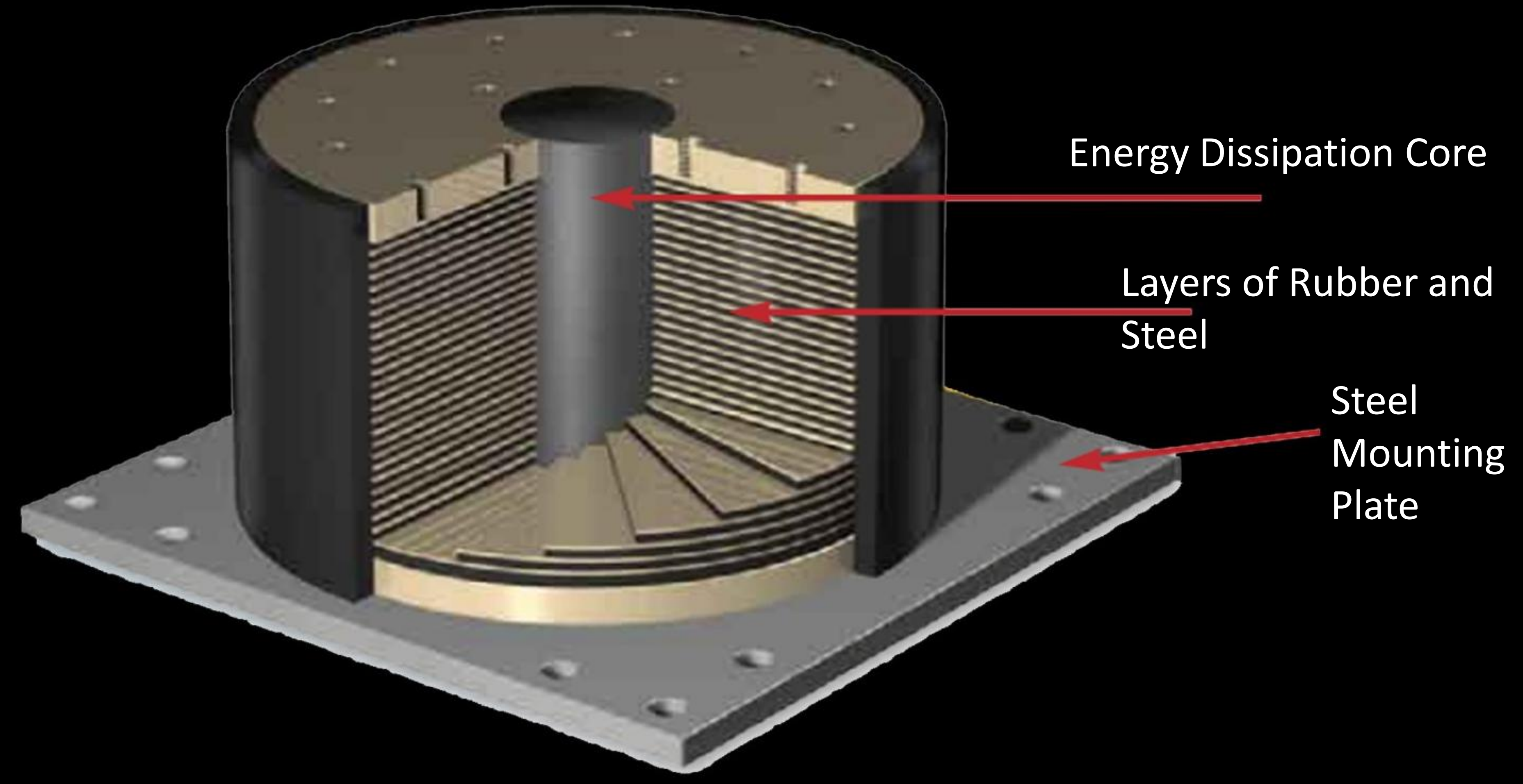
Base Isolation Design Process

- **Design Process:**
  - Hysteresis curve to obtain characteristics of isolators (could not obtain one)
  - Preliminary sizing designed assuming an effective period at design displacement and maximum displacement
  - Isolator damping properties (roughly 10 – 20%)
  - Obtained lateral forces for preliminary trial
  - Reiterated to obtain drifts adequate for S-1 performance requirements

Preliminary Sizing



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Preliminary Sizing

$$\beta_D = \frac{1}{2\pi}\left[\frac{total\ area\ of\ hysteresis\ loop}{K_{D,MAX}\ D^2}\right] \qquad \beta_M = \frac{1}{2\pi}\left[\frac{total\ area\ of\ hysteresis\ loop}{K_{M,MAX}\ D^2}\right]$$

$$T_D = 2\pi\sqrt{\frac{W}{k_{D,MIN}\,g}} \qquad T_M = 2\pi\sqrt{\frac{W}{k_{M,MIN}\,g}}$$

$$D_D = \frac{gS_{D1}T_D}{4\pi^2 B_D} \qquad D_M = \frac{gS_{M1}T_M}{4\pi^2 B_M}$$

$$V_b = k_{D,MAX}D_D \qquad V_S = \frac{k_{D,MAX}D_D}{R_I}$$

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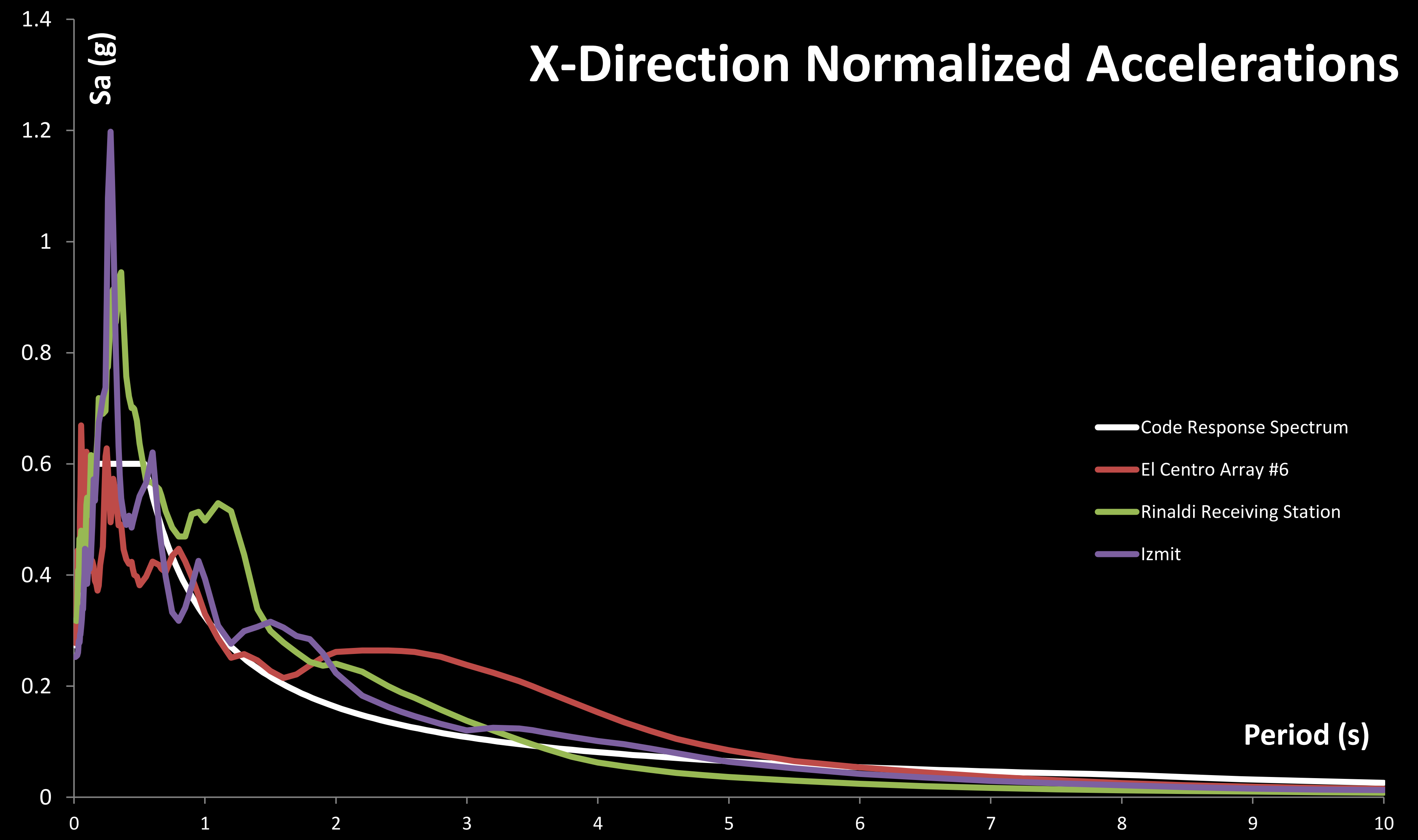
Earthquake Scaling

- **Earthquake history records were selected and scaled for a nonlinear time history analysis (MAE Incorporation – *AE 538*)**
  - Recommendations from FEMA P695
  - Scaling was done for the response of the building in Sacramento, CA
  - Applied simultaneously in both directions due to torsional irregularity
  - PEER NGA (Pacific Engineering Earthquake Research)

Normalized Accelerations



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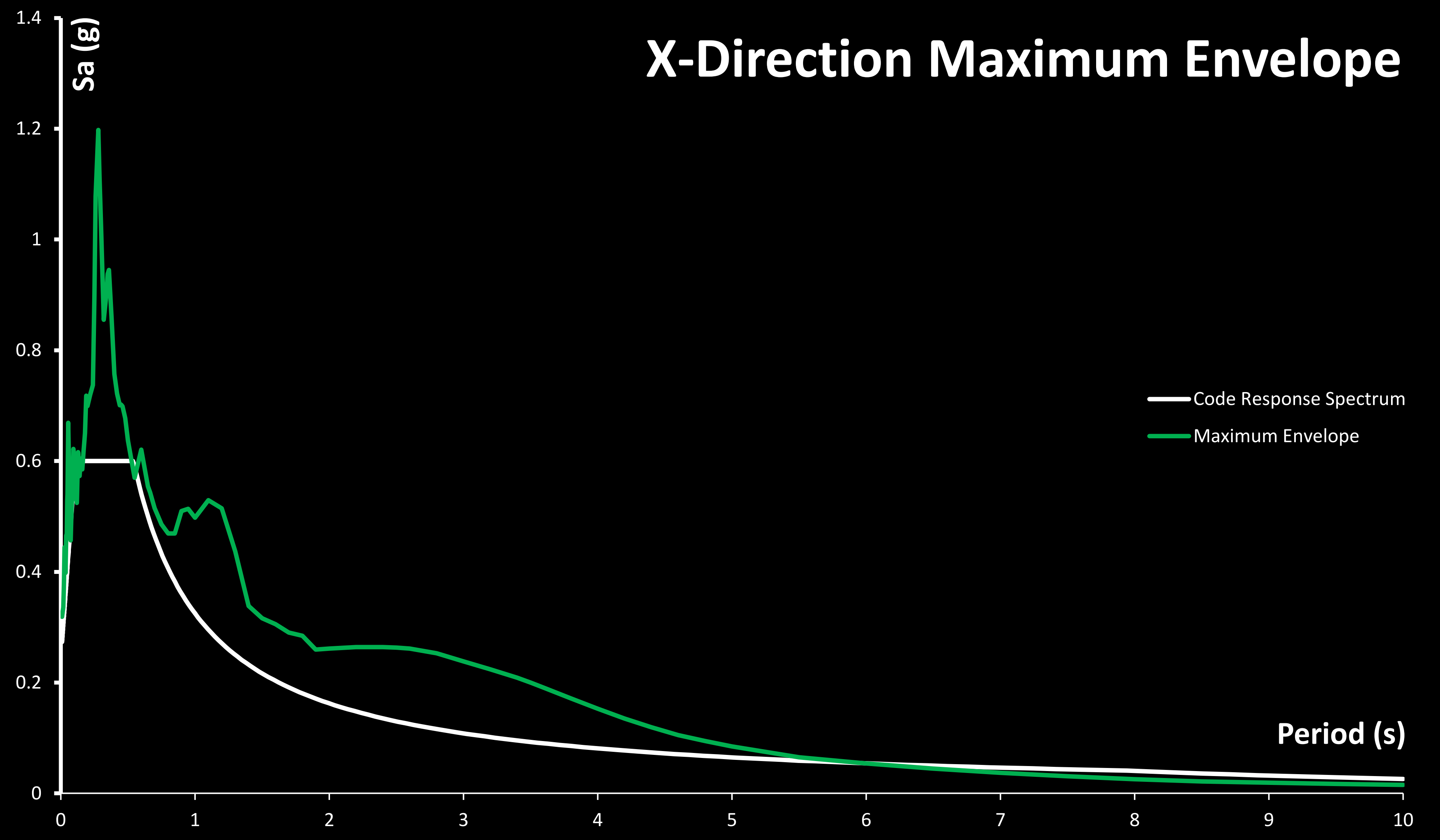

South Patient Tower

Base Isolation System

- **Nonlinear properties modeled in ETABS**

Isolator Properties		
Vertical Effective Stiffness	16000	k/in
Horizontal Effective Striffness	6	k/in
Nonlinear Stiffness	60	k/in
Yield Strength	37.5	k
Post Yield Stiffness Ratio	0.2	
Effective Damping	15%	

El Centro Array #6 - Maximum Displacements/Drifts

	Level	δ_{XE}	Δ_X	S-3 Δ_a (1.0%)	S-1 Δ_a (0.5%)	S-3 Met	S-1 Met
T = 4.51 sec., K_{vert} = 16000 k/in., K_{linear} = 6 k/in., $K_{nonlinear}$ = 60 k/in., Yield Strength = 37.5 k, Post Yield Stiffness Ratio = 0.2	Penthouse/Roof	25.5	0.7	1.88	0.94	Yes	Yes
	11th	24.8	0.6	1.36	0.68	Yes	Yes
	10th	24.2	0.6	1.36	0.68	Yes	Yes
	9th	23.6	0.6	1.36	0.68	Yes	Yes
	8th	22.9	0.68	1.36	0.68	Yes	Yes
	7th	22.3	0.67	1.36	0.68	Yes	Yes
	6th	21.6	0.68	1.68	0.84	Yes	Yes
	5th	20.9	0.68	1.36	0.68	Yes	Yes
	4th	20.2	0.67	1.36	0.68	Yes	Yes
	3rd	19.6	0.63	1.36	0.68	Yes	Yes
	2nd	18.9	0.8	1.68	0.84	Yes	Yes
	1st	18.1	0.6	1.28	0.64	Yes	Yes
	Ground	17.5	N/A	N/A	N/A	N/A	N/A

Final Size

Isolator Diameter, D_I (in)	DESIGN PROPERTIES			Maximum Displacement, D_{max}(in)	Axial Load Capacity, P_{max}(kips)
	Yielded Stiffness, K_d(k/in)	Characteristic Strength, Q_d(kips)	Compression Stiffness, K_v(k/in)		
12.0	1-5	0-15	>250	6	100
14.0	1-7	0-15	>500	6	150
16.0	2-9	0-25	>500	8	200
18.0	2-11	0-25	>500	10	250
20.5	2-13	0-40	>1,000	12	300
22.5	3-16	0-40	>3,000	14	400
25.5	3-20	0-50	>4,000	16	600
27.5	3-24	0-50	>4,500	18	700
29.5	4-27	0-60	>5,000	18	800
31.5	4-30	0-60	>6,000	20	900
33.5	4-35	0-80	>7,000	22	1,100
35.5	4-35	0-80	>8,000	22	1,300
37.5	4-35	0-110	>10,000	24	1,500
39.5	5-36	0-110	>11,000	26	1,700
41.5	5-36	0-130	>12,000	28	1,900
45.5	6-37	0-150	>16,000	30	3,100
49.5	7-38	0-170	>21,000	32	4,600
53.5	8-40	0-200	>29,000	34	6,200
57.1	9-41	0-230	>30,000	36	7,500
61.0	10-42	0-230	>37,000	36	9,000

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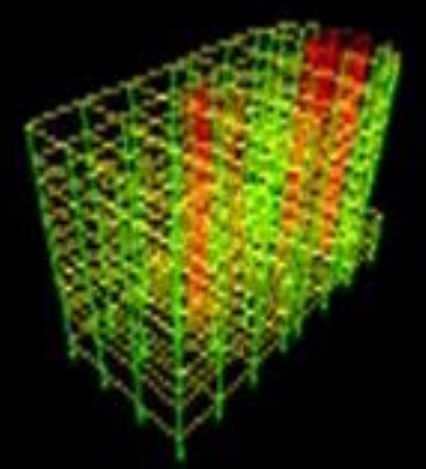
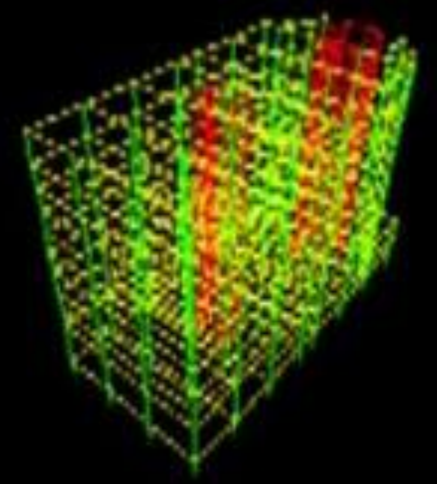


Fixed Structure



Isolated

Comparison of Systems

Summary of Systems		
	Fixed Base Structure (CA - Fixed Model)	Isolated Structure (CA - Base Isolation Model)
Moment Frame Sizes	24" x 36"	24" x 24"
Shear Wall Thickness	16"	12"
Maximum Drift Value	0.836 in.	0.8 in.

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Construction Management

- **Isolator Impact**
  - D = 45.5”
  - Material Costs Per Device = $16,204
  - Total Isolation Costs = $1,070,370
- **Difference between CA – Fixed Model and CA – Base Isolation Model = $684,300**
- **Additional Costs**
  - Seismic Moat Wall
  - Flexible MEP Connections
  - Design and Testing/Inspection Costs

Costs

Isolator Costs			
Base Isolator Costs			
Isolator (45.5")	Costs:	$	972,240
Installation Costs			
1 Crane - 2000lb	Costs:	$	74,250
Labor Costs			
2 Laborers	Costs:	$	15,888
1 Crane Operater	Costs:	$	7,992
		$	**1,070,370**

Summary of Costs			
	Without Location Factor	With Location Factor	Difference With Base Model
Original Structure	$5,250,302	N/A	-
Fixed Base System	$5,773,200	$6,344,747	$1,094,445
Isolated Structure	$6,395,851	$7,029,040	$1,778,738

South Patient Tower

Construction Management

Durations

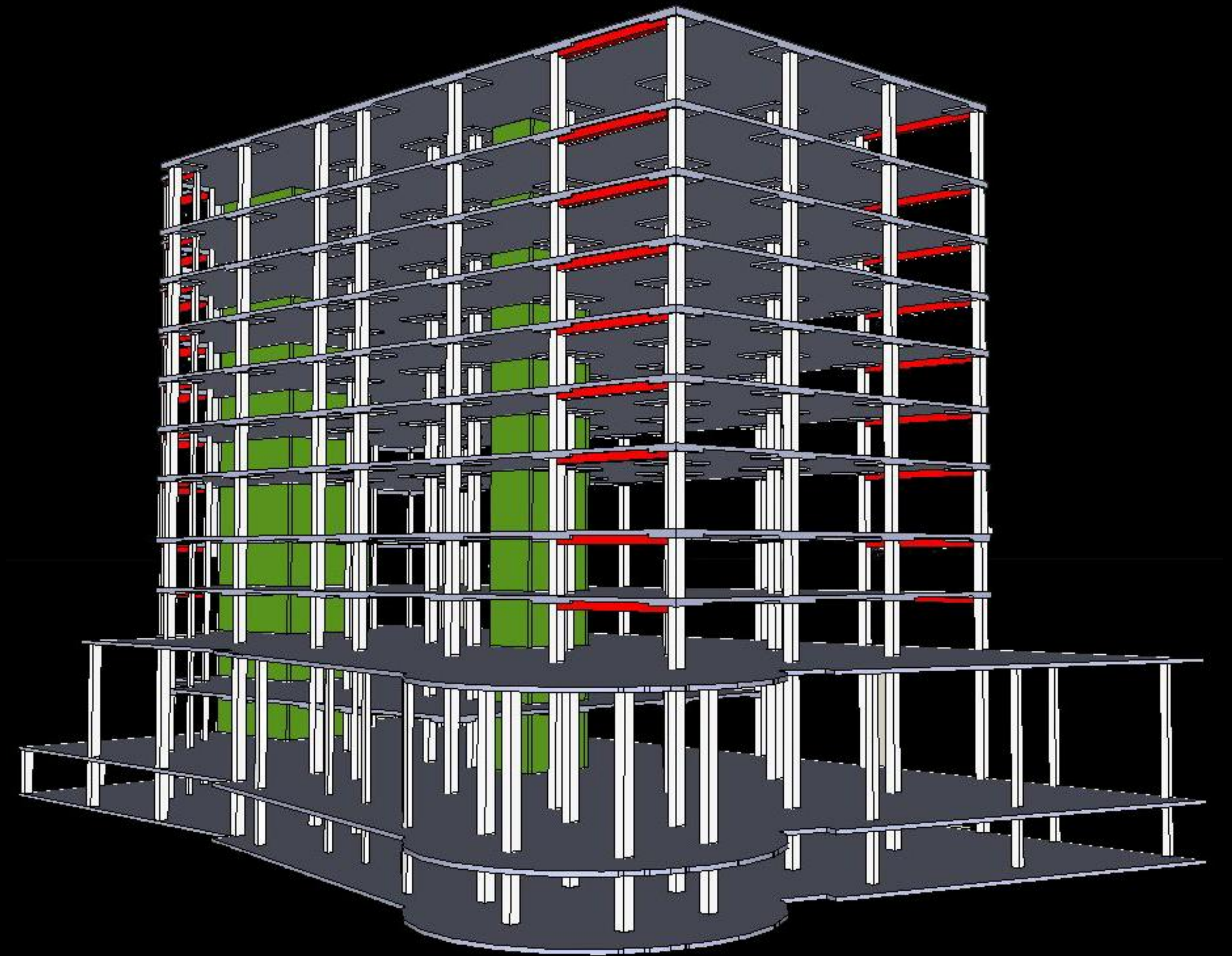
- **Isolator Impact**
  - Roughly 6 weeks for start of delivery
  - 12 – 15 weeks for total project lead time

Summary of Durations	
	Duration (Months)
Original Structure	15
Fixed Base System	18
Isolated Structure	19

South Patient Tower

Conclusions

- Base isolation is a very efficient method of increasing the performance of the structure
- Cost minimal in comparison to cost of replacing damaged structural components following a significant earthquake
- Minimize hospital room operational losses
    - Building Enclosure
- Mitigate damage to expensive hospital equipment



South Patient Tower

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  - Professor Robert Holland
- Entire AE Student Body (My social life has been *isolated* due to thesis © David Tran)
- Family and Friends

Questions?