Optimization of the Foundation & Lateral Systems

St. Vincent Mercy Medical Center Heart Pavilion
Toledo, Ohio

Kristen M. Lechner
Structural Option

AE Senior Thesis
April 13, 2009
The Pennsylvania State University

Presentation Outline

- Project Information
- Existing Structural System
- Problem Statement & Solution
- Structural Redesign
- Construction Management Study
- Recommendations

General Information

- 4 Story Hospital
- Addition to St. Vincent Mercy Medical Center Campus
- Project Cost = $45 Million
- Project Size = 144,000 S.F.
- Owner: St. Vincent Mercy Medical Center
- Project Deliver Method: Design-Build
- Groundbreaking: August 2005
- Completion: August 2007

Project Location

The Heart Pavilion was constructed for St. Vincent's Mercy Medical Center Campus, established in 1855.

Building Architecture

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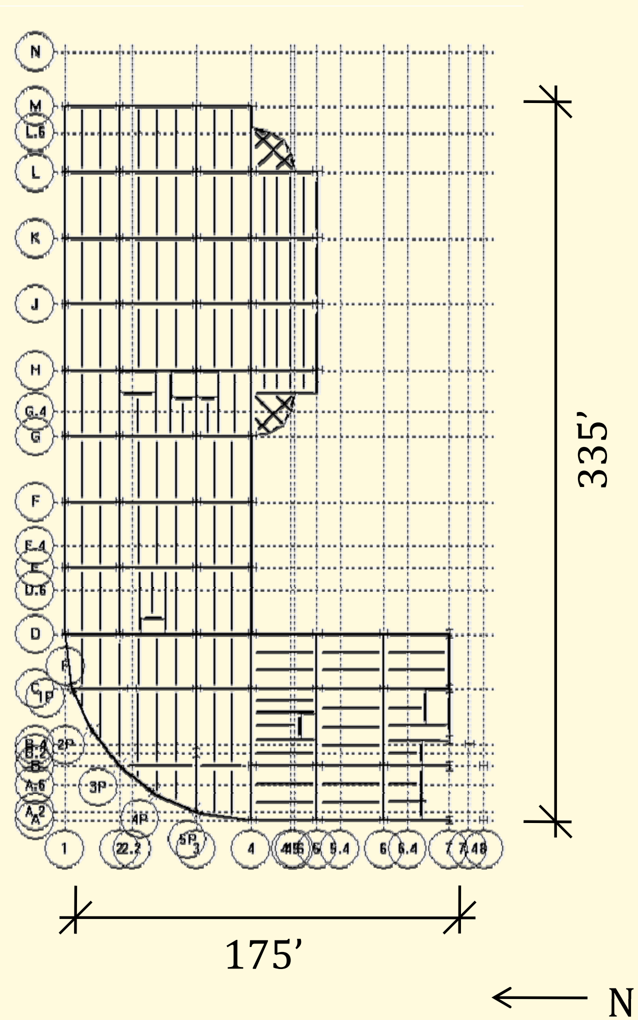
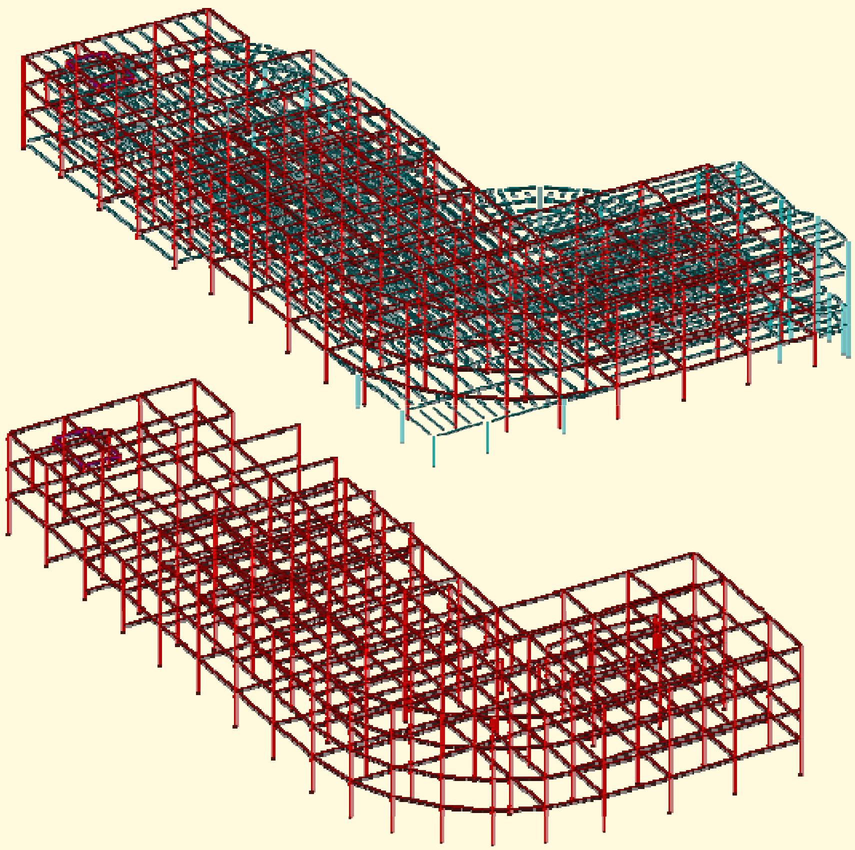
Gravity System

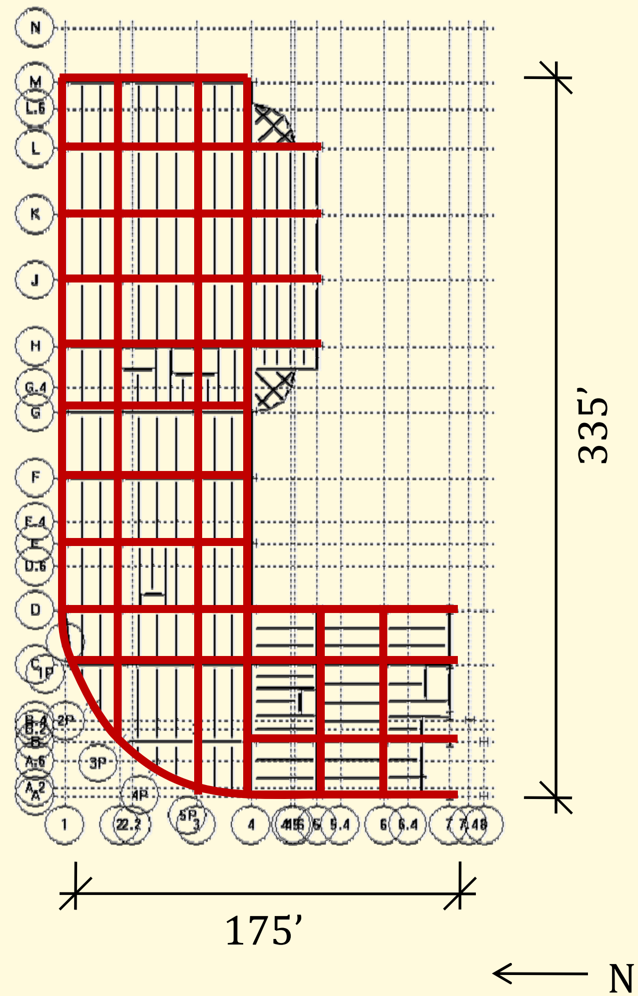
- Composite Steel Framing and NWC
- Typical 14’-0” floor to floor height
- Foundation: 80 drilled caissons



Lateral Force Resisting System

- Non-Seismic Steel Moment Frames





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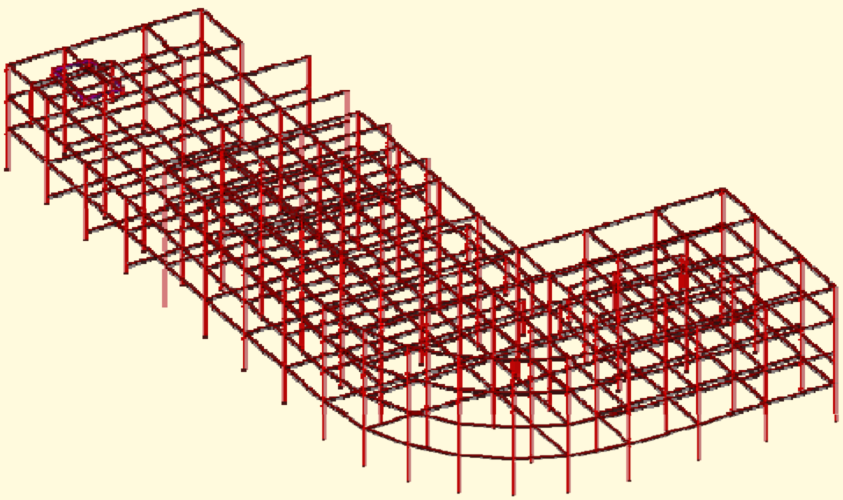
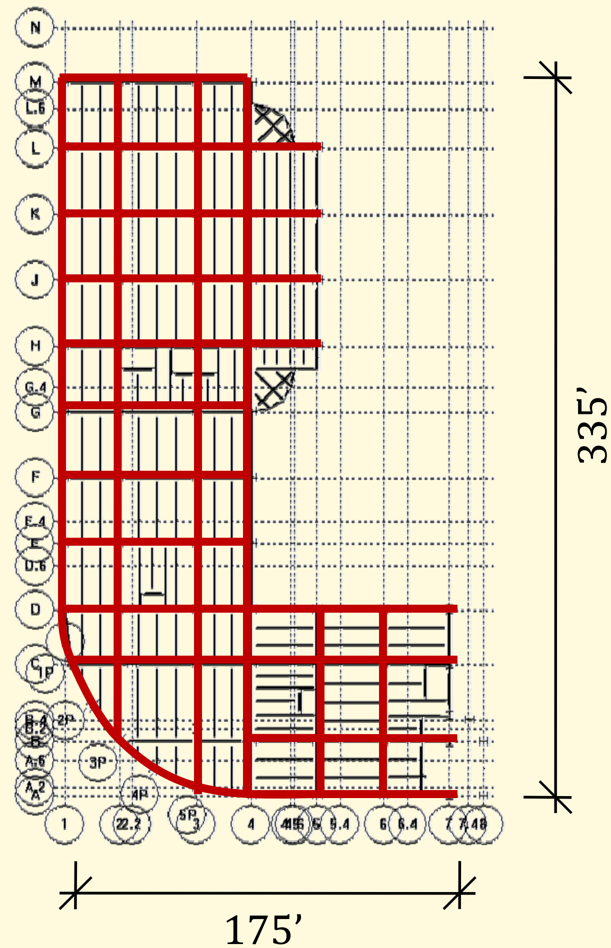
Problem Statement

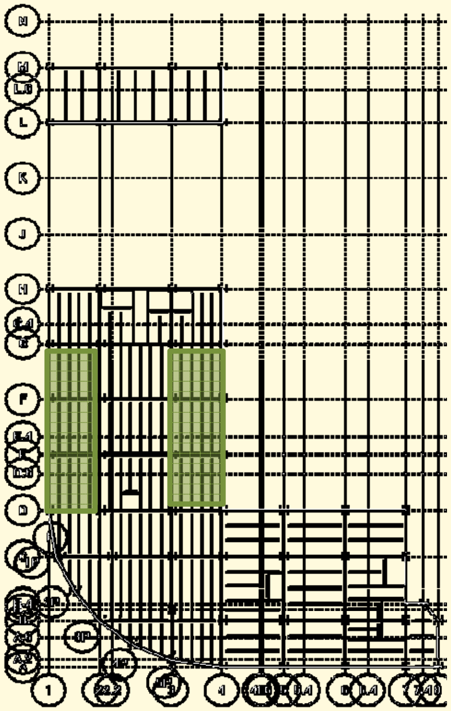
- Existing Lateral System



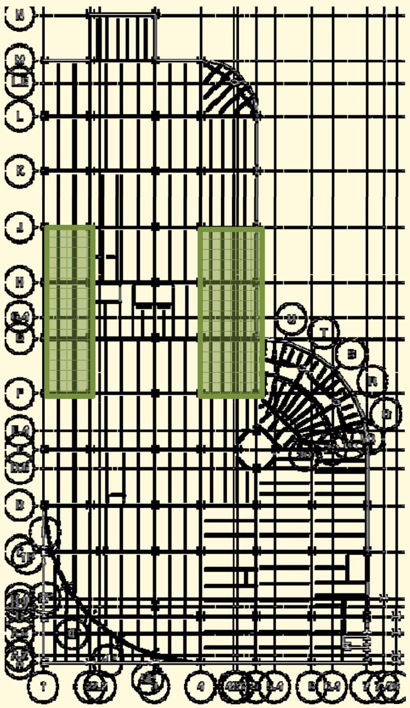


Problem Statement

- Vibration Criteria for Operating Rooms



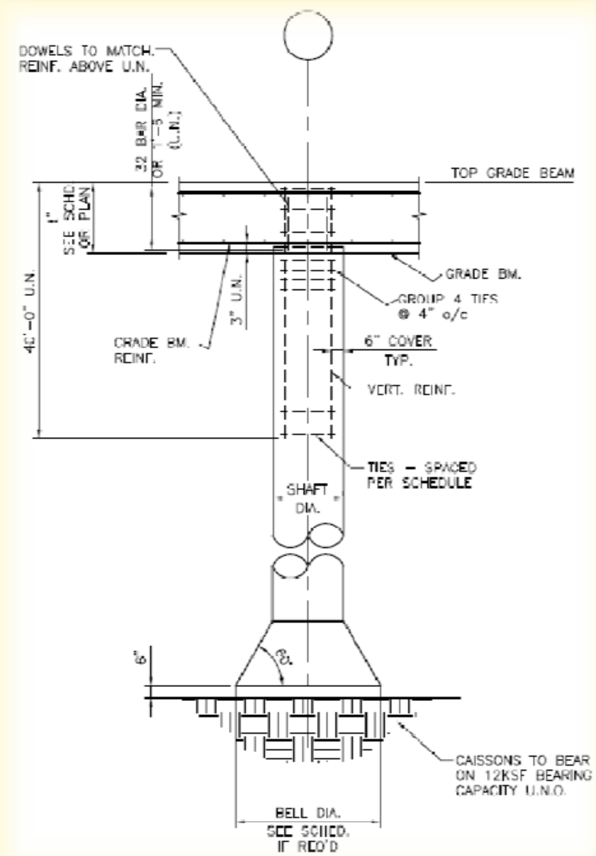
Original Surgery Suite on 3rd Floor



Existing Surgery Suite on 1st Floor

Problem Statement

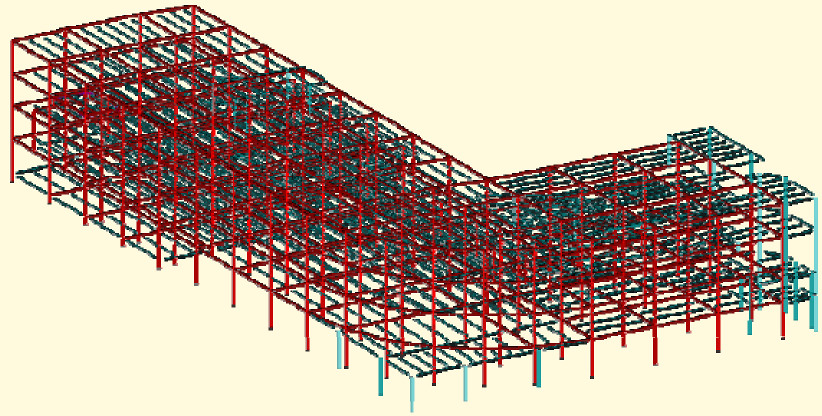
- Drilled Caisson Foundation System



Design Goals

- Reduce number of steel moment frames utilizing seismic detailing
- Decrease the base shear value by reducing the tonnage of steel
- Reduce cost & construction time by using fewer frames of a more complex system
- Improve serviceability of O.R. spaces by redesigning for vibration criteria
- Improve soil conditions by implementing a Geopier Intermediate Foundation System

M.A.E. Acknowledgement



- Utilize knowledge of structural computer modeling to build RAM Model (AE 597A)

- Expand upon basic connection design principles to detail seismic connections (AE 534)

Breadth Acknowledgement

Breadth Study I: Façade Study

Existing **Redesigned**

View from Entrance

View from Main Street

Breadth Acknowledgement

Breadth Study II: Construction Management Study

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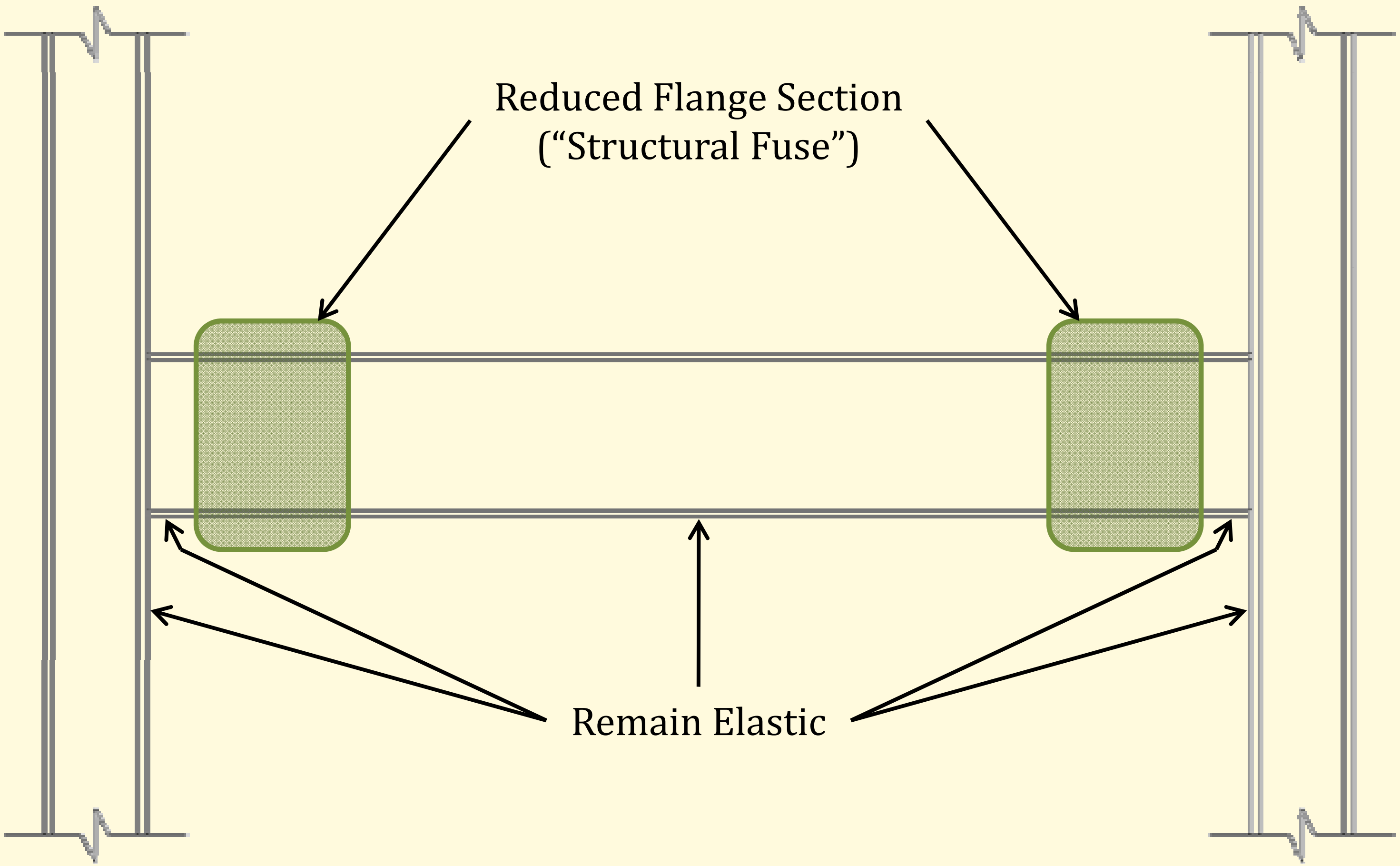
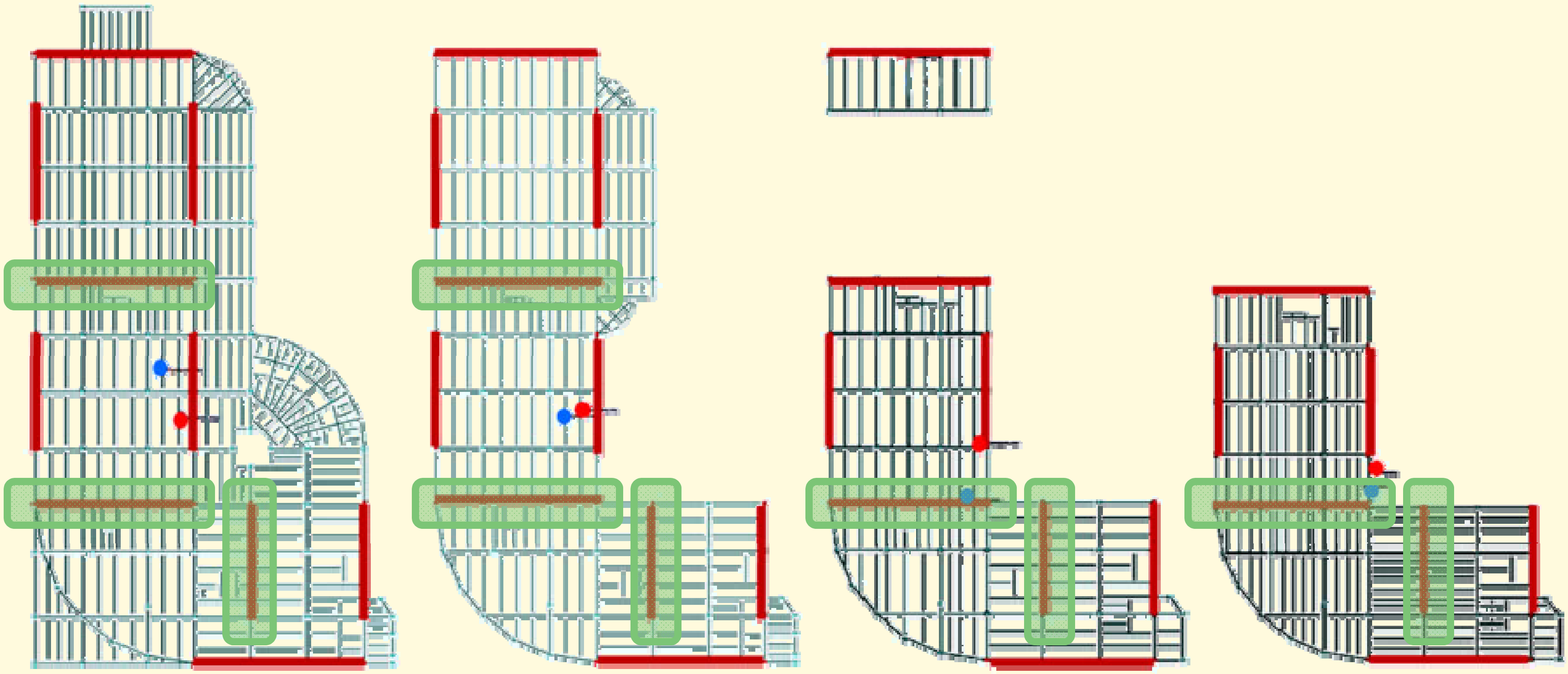
SMF Design Concept



SMF Design Considerations

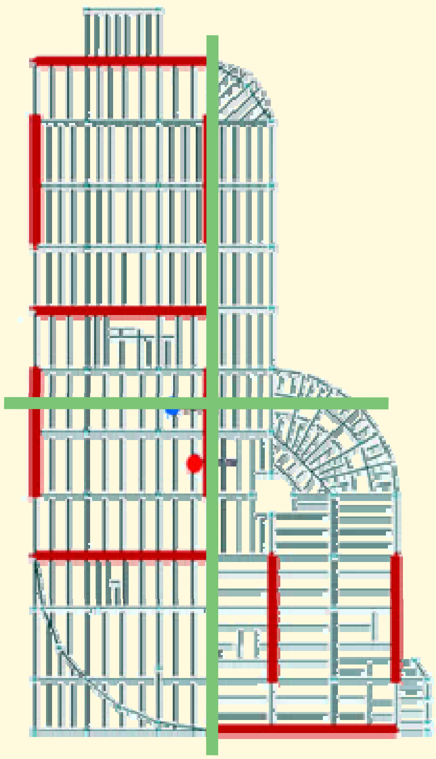
- Minimize number of SMF's along interior



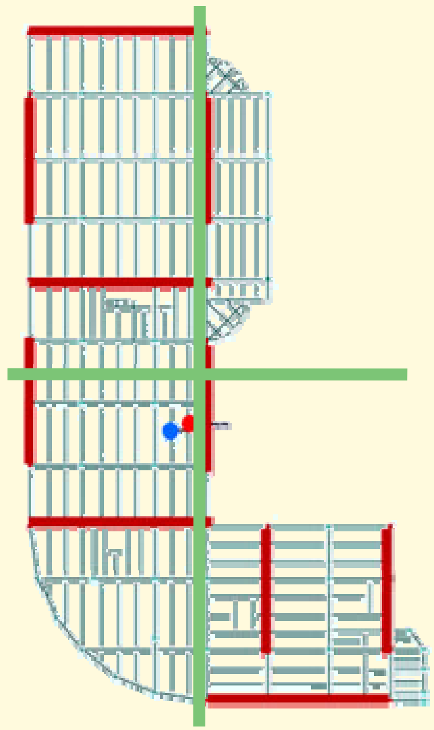
1st Floor *2nd Floor* *3rd Floor* *Roof*

SMF Design Considerations

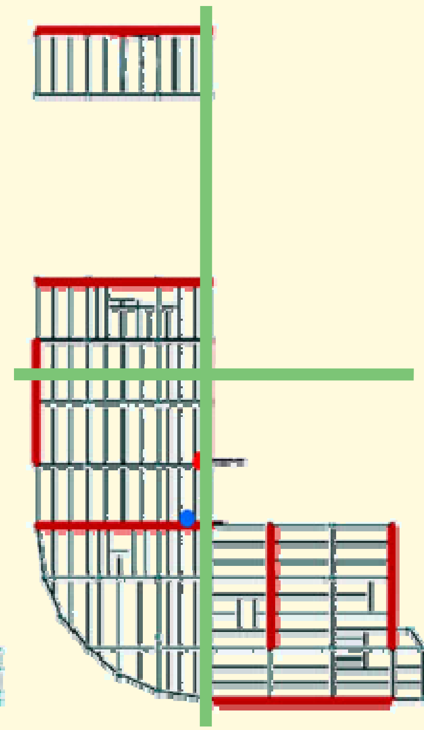
- Keep layout symmetrical



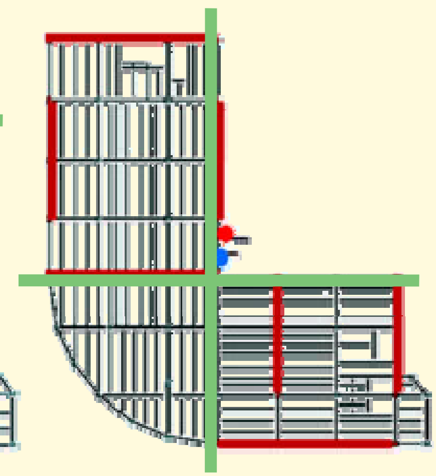
1st Floor



2nd Floor



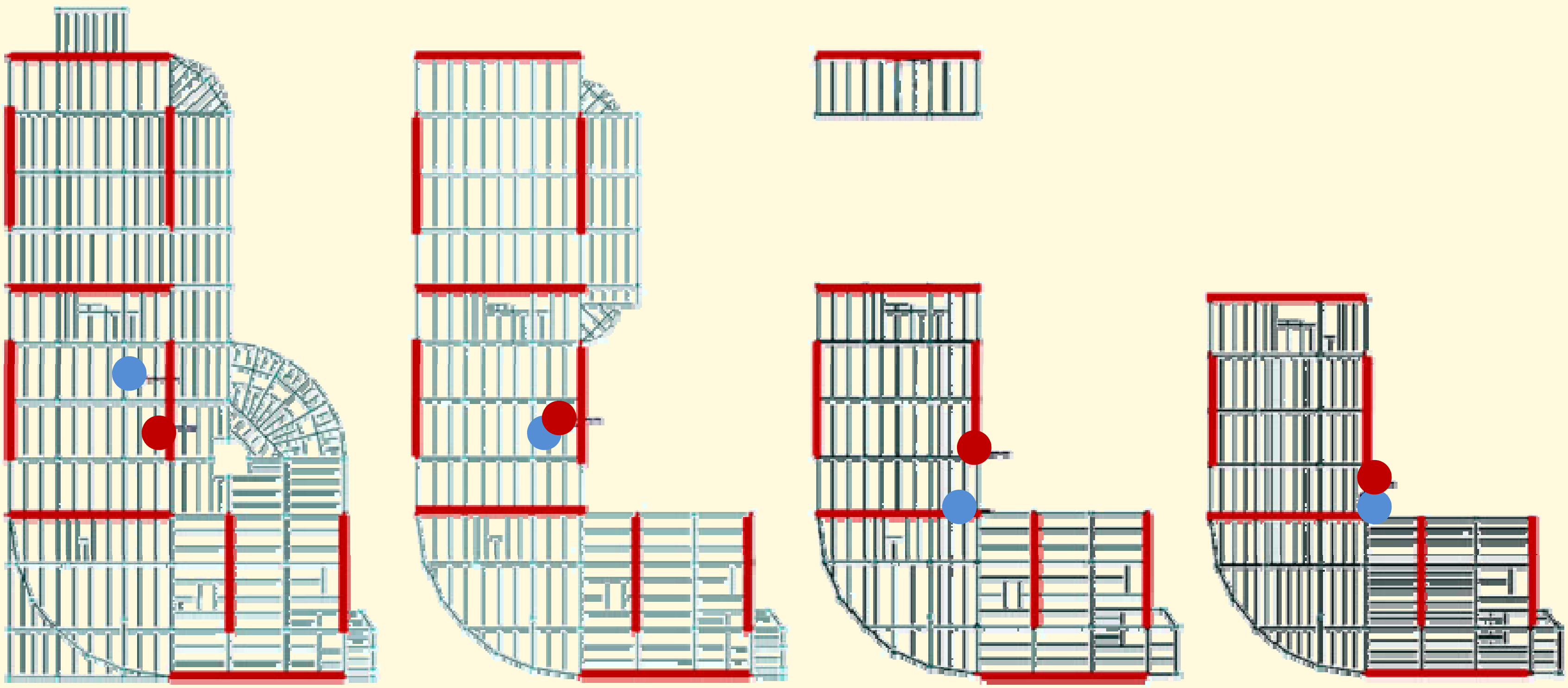
3rd Floor



Roof

SMF Design Considerations

- Orient SMF's to keep COM & COR as close as possible



1st Floor *2nd Floor* *3rd Floor* *Roof*

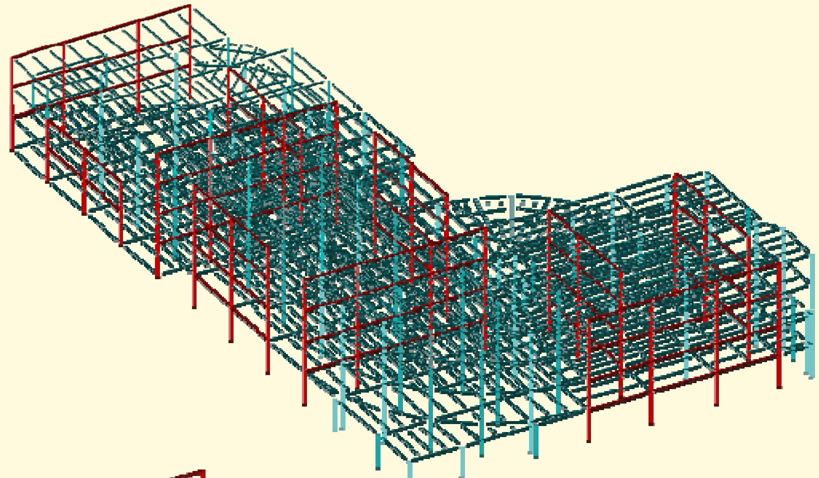
SMF Design Process

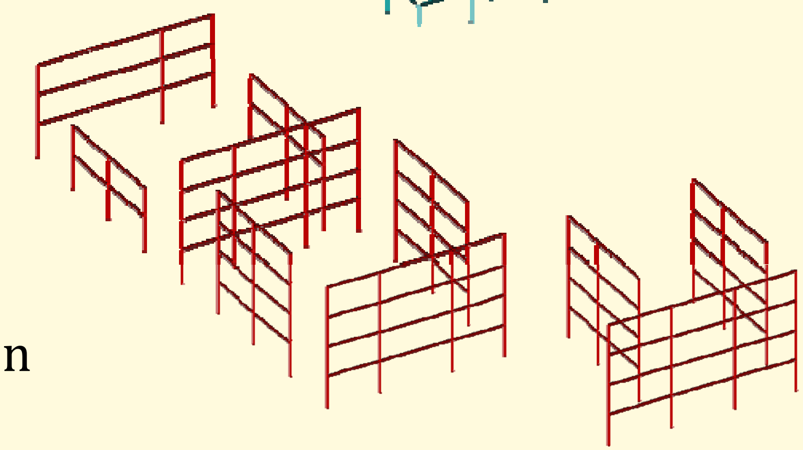
	Existing Lateral System	SMF Lateral System
R	3	8
Cs	0.092	0.034
Story Forces (k)		
Roof	241	118
3	436	228
2	275	206
1	149	125
Base Shear (k)	**1100**	**678**

The SMF System reduces approximately **38 %** of the base shear!

RAM Structural System Model

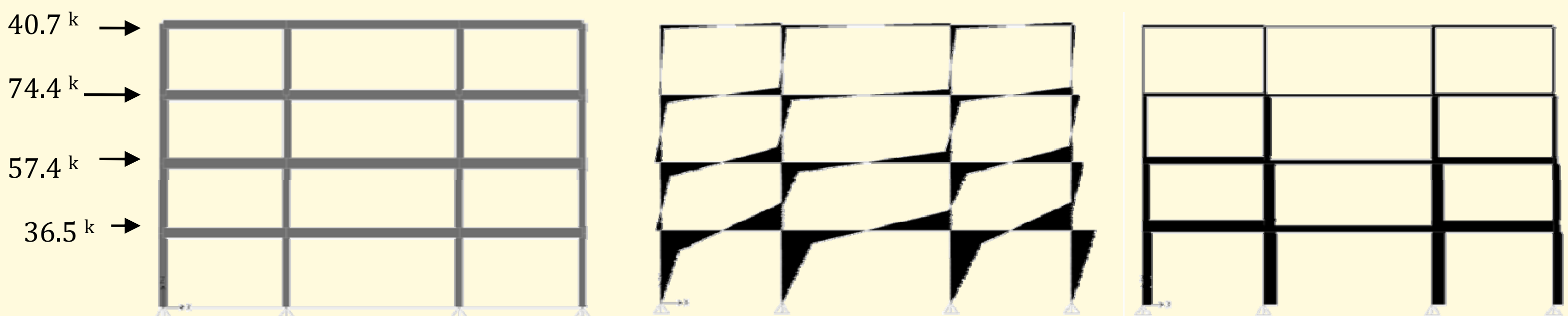
- Assumptions
  - A rigid diaphragm assigned to every floor
  - Columns pinned at the base
  - Beams & Columns fixed-fixed within SMF's
  - 5% eccentricity applied to account for accidental torsion
  - P-delta effects automatically taken into account



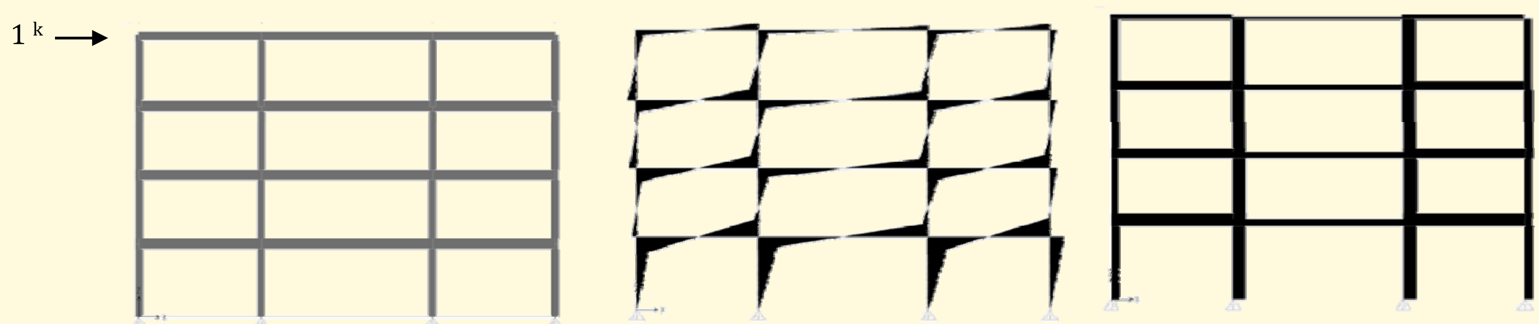


Member Optimization

- Real Case



- Virtual Case



Member Contribution- Beams

	Member	E (ksi)	I_x (in^4)	M_i (ft-k)	m_i (ft-k)	L_i (ft)	$\Delta_i=1/3\,(M_i m_i L_i^3)/(EI_i L_i^2) + (F_i f_i L_i)/(AE)$	Member Contribution
L. Beams	1	29000	2700	741	3.88	25	0.00031	8.66%
	2	29000	2700	435	2.96	25	0.00014	3.88%
	3	29000	1830	213	2.69	25	0.00009	2.55%
	Roof	29000	843	68	1.42	25	0.00003	0.93%
Middle Beams	1	29000	2700	518	2.75	35	0.00021	6.01%
	2	29000	2700	309	2.13	35	0.00010	2.78%
	3	29000	1830	151	1.82	35	0.00006	1.71%
	Roof	29000	843	51	0.92	35	0.00002	0.63%
Rt. Beams	1	29000	2700	734	3.89	25	0.00030	8.60%
	2	29000	2700	426	2.98	25	0.00014	3.83%
	3	29000	1830	210	2.51	25	0.00008	2.34%
	Roof	29000	843	70	1.23	25	0.00003	0.83%

Frame 3	Member		E (ksi)	A (in^2)	F_i (k)	f_i (k)	L_i (ft)	$\Delta_i=1/3\,(M_i m_i L_i^3)/(EI_i L_i^2) + (F_i f_i L_i)/(AE)$	Member Contribution
	Col D-1	1	29000	56.8	12	0.03	15	0.00031	8.75%
		2	29000	56.8	7	-0.01	14	0.00014	3.86%
		3	29000	42.7	17	-0.03	14	0.00008	2.39%
		Roof	29000	42.7	7	0.21	14.5	0.00005	1.42%
	Col D-2	1	29000	75.6	7	-0.03	15	0.00021	5.97%
		2	29000	75.6	21	0.02	14	0.00010	2.85%
		3	29000	51.8	22	-0.01	14	0.00006	1.65%
		Roof	29000	51.8	13	0.32	14.5	0.00006	1.80%
	Col D-3	1	29000	75.6	7	-0.03	15	0.00021	5.97%
		2	29000	75.6	22	0.02	14	0.00010	2.86%
		3	29000	51.8	21	0.02	14	0.00006	1.82%
		Roof	29000	51.8	14	0.29	14.5	0.00006	1.72%
	Col D-4	1	29000	56.8	11	0.03	15	0.00031	8.69%
		2	29000	56.8	8	-0.03	14	0.00013	3.77%
		3	29000	42.7	15	0.03	14	0.00009	2.48%
		Roof	29000	42.7	7	0.17	14.5	0.00004	1.23%
					$\sum=$	1.00		$\sum \Delta_i=$ 0.00538	100%

Beams	42.8%
Col D-1	16.4%
Col D-2	12.3%
Col D-3	12.4%
Col D-4	16.2%

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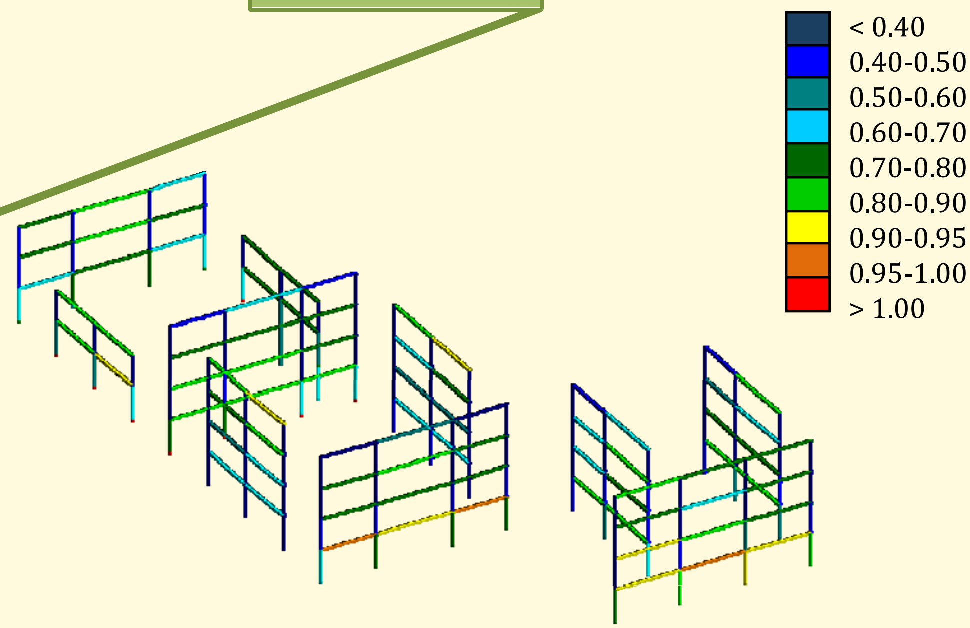
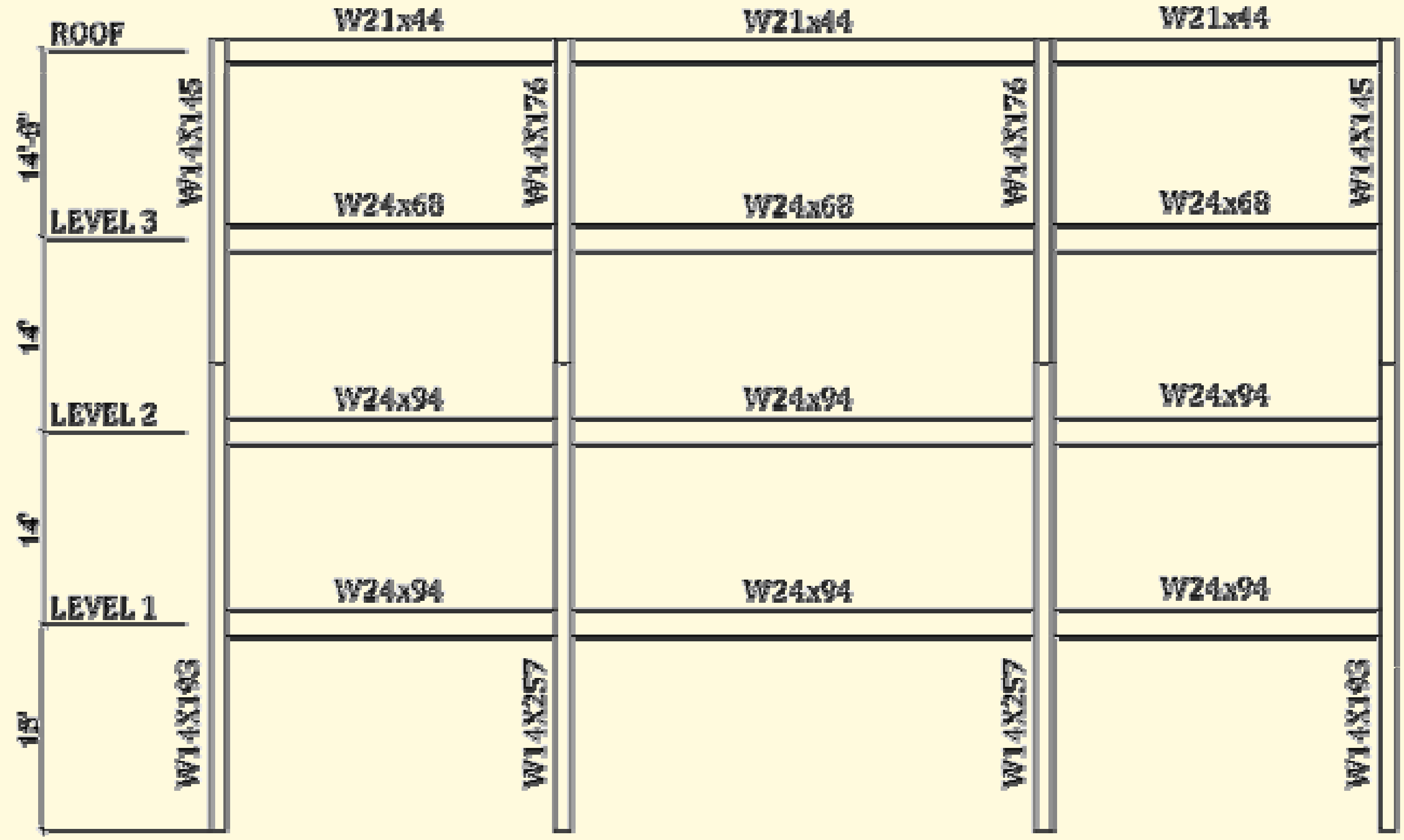
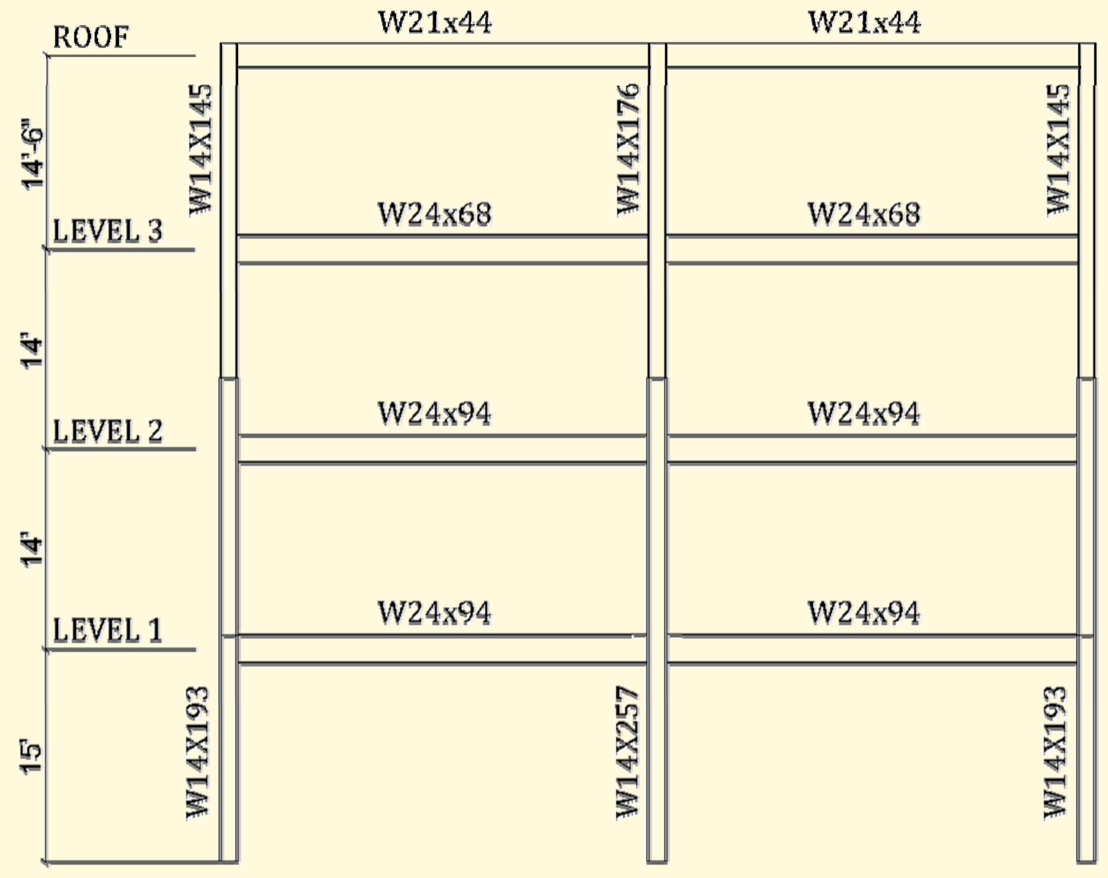


Typical SMF Sizes



Typical SMF in X-Direction

Typical SMF Sizes

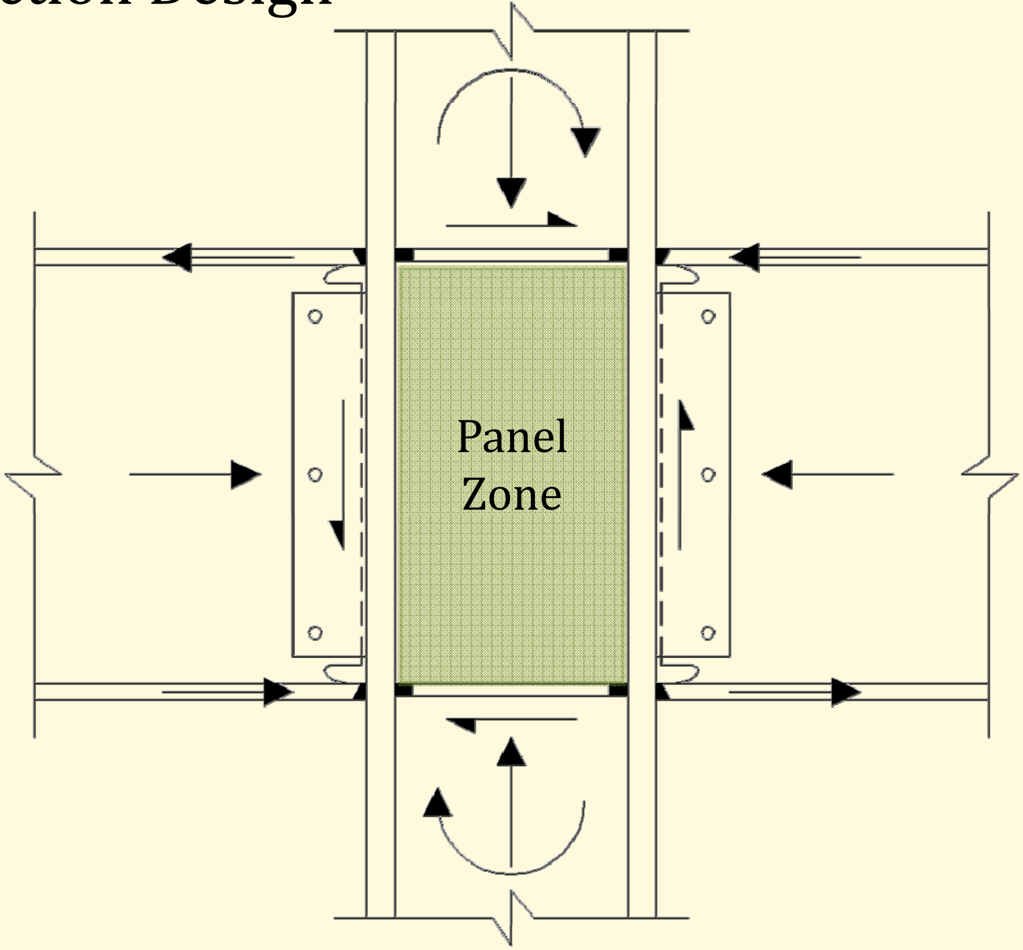


Typical SMF in Y-Direction

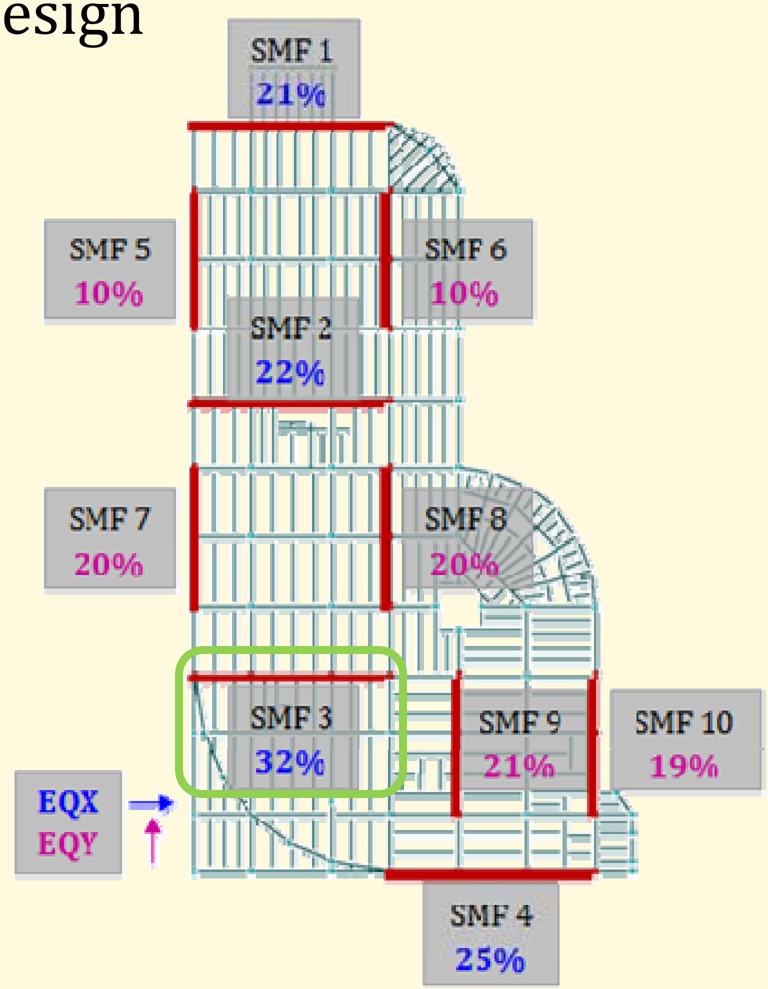
RBS Connection Design

- Four basic design concerns:
  - Determining the moment at the plastic hinge of the beam
  - Determining the moment at the column face
  - Ensuring the “strong column-weak beam” criterion is met
  - Ensuring the panel zone strength of the column is adequate

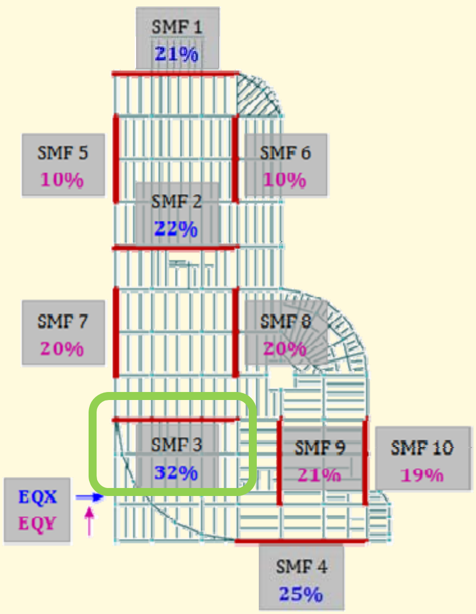
RBS Connection Design

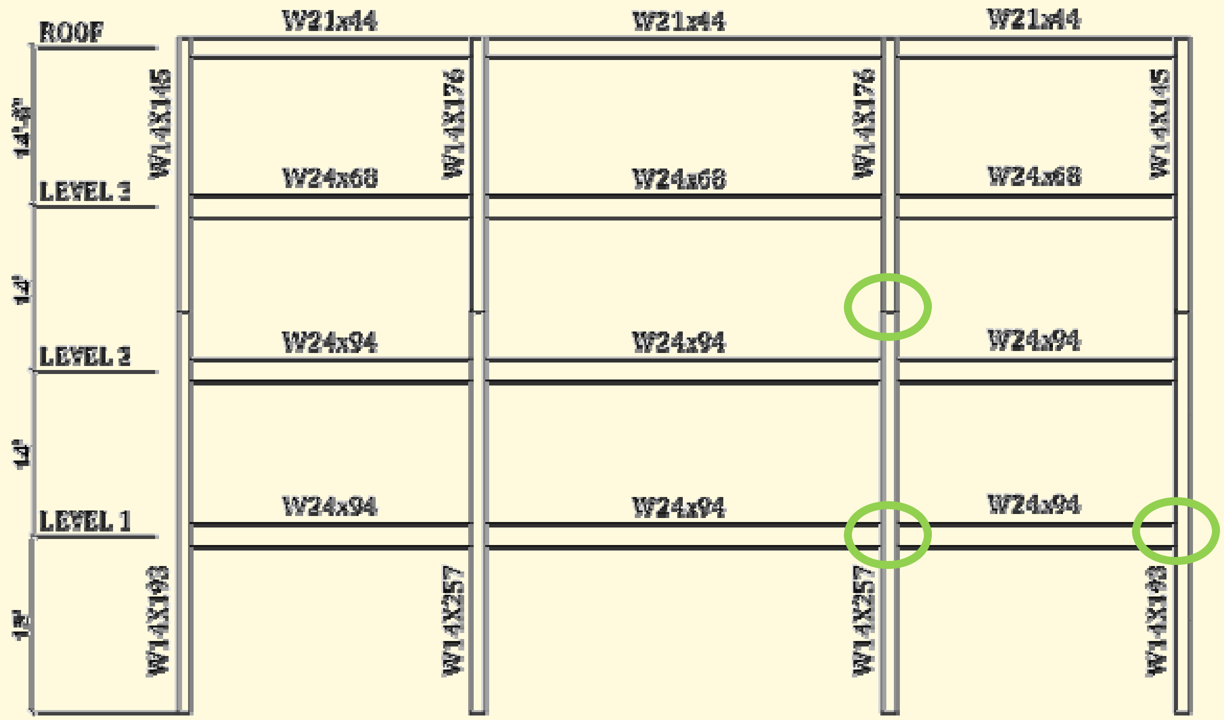


RBS Connection Design



RBS Connection Design

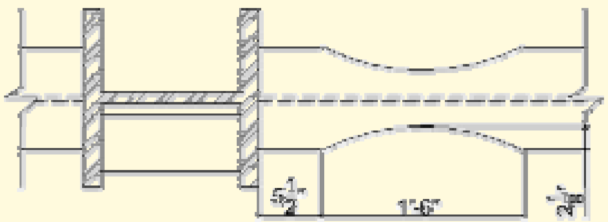


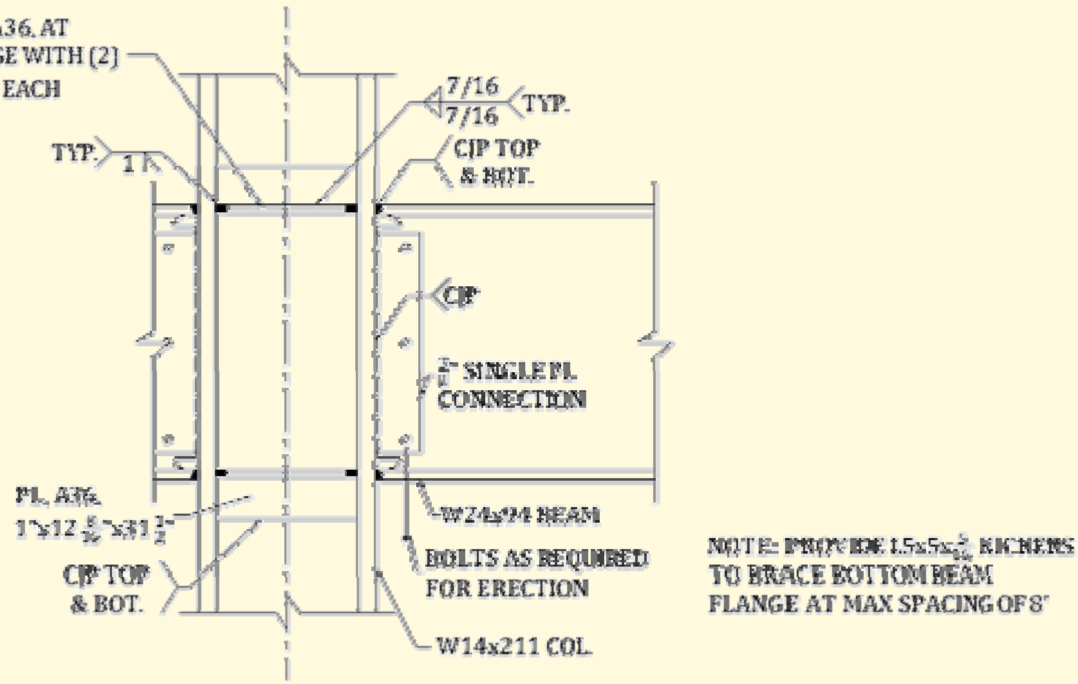


Elevation of SMF 3

RBS Connection Design

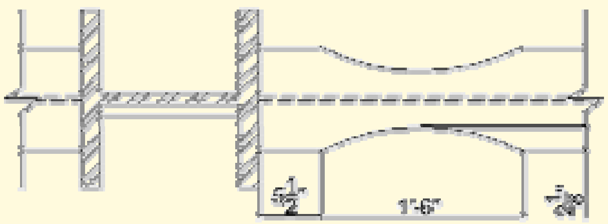
- Interior Alternative I

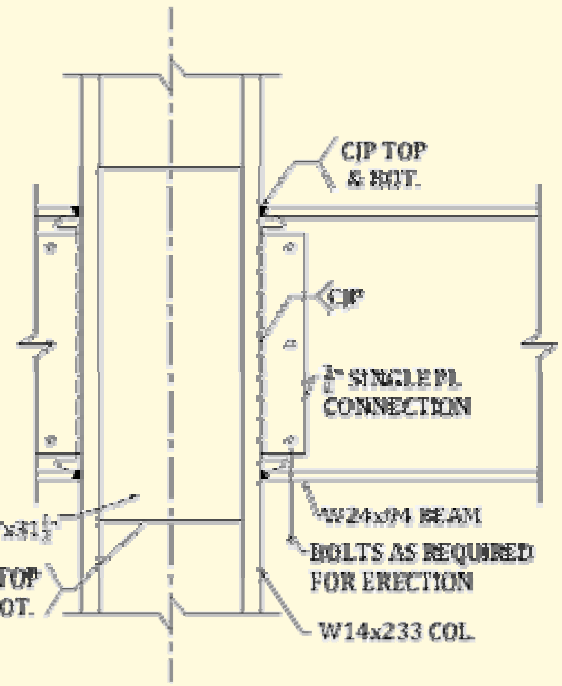




RBS Connection Design

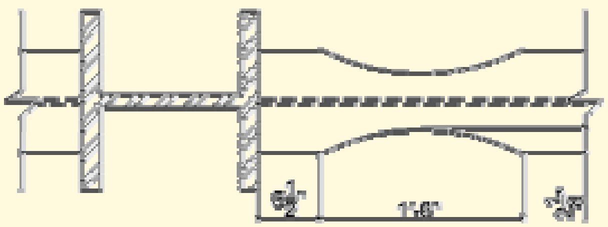
- Interior Alternative II

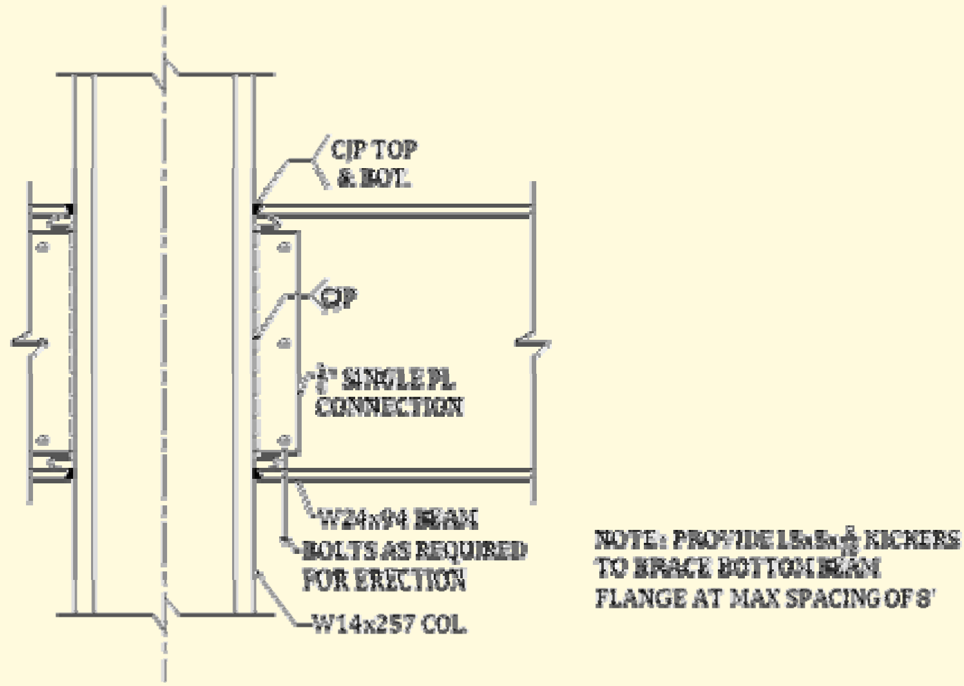




RBS Connection Design

- Interior Alternative III





RBS Connection Selection Based on Economy

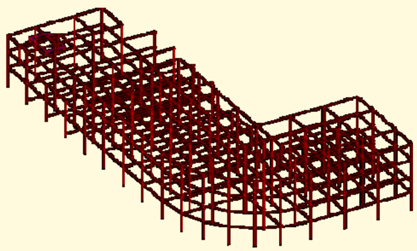
Total Cost per Connection

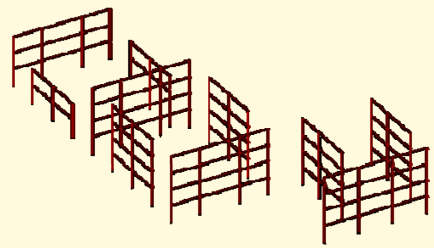
Configuration	Equiv. Wt. of Steel Cost ($)	Fabrication Cost ($)	Installation Cost ($)	Total Cost
Alternative I	8,505	347	2,135	$10,987
Alternative II	8,978	279	1,365	$10,622
Alternative III	9,540	216	630	$10,386

Using a W14x257 column size is more economical!

SMF Design Conclusions

- Number of moment frames significantly reduced ✓





- Tonnage of steel reduced ✓

Lateral System	Tonnage of Steel	Density of Steel (psf)
Existing System	610	7.98
Redesigned System	248	3.22

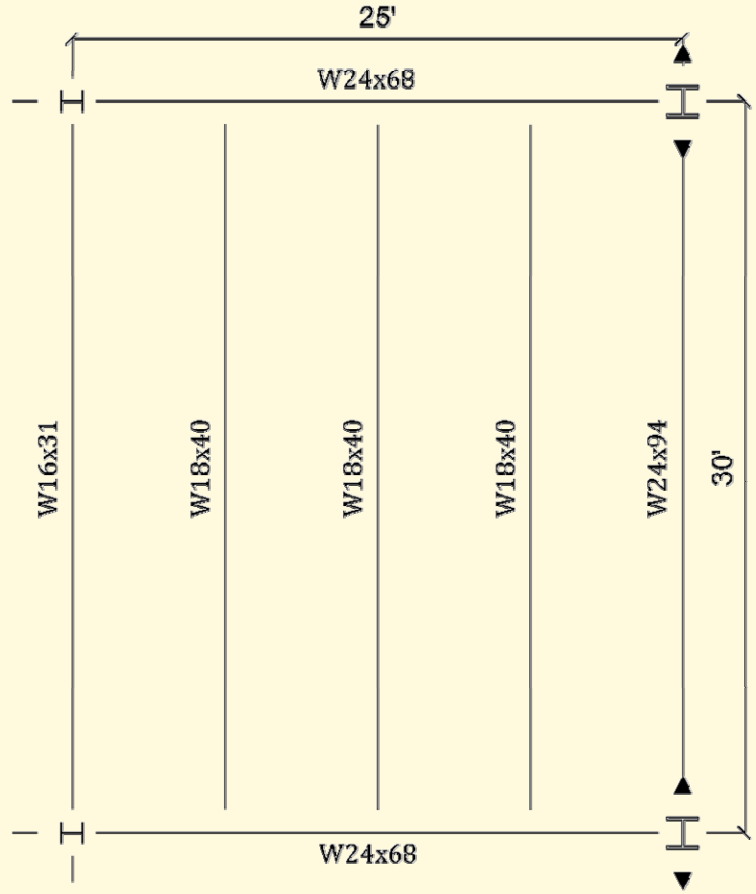
- Base Shear value reduced by 38% ✓

Surgery Space Redesign

- Assumptions:
  - Weight of person = 185 lbs
  - Walking velocity = 100 steps/min
- Vibrational velocity limit = 8000μin/sec

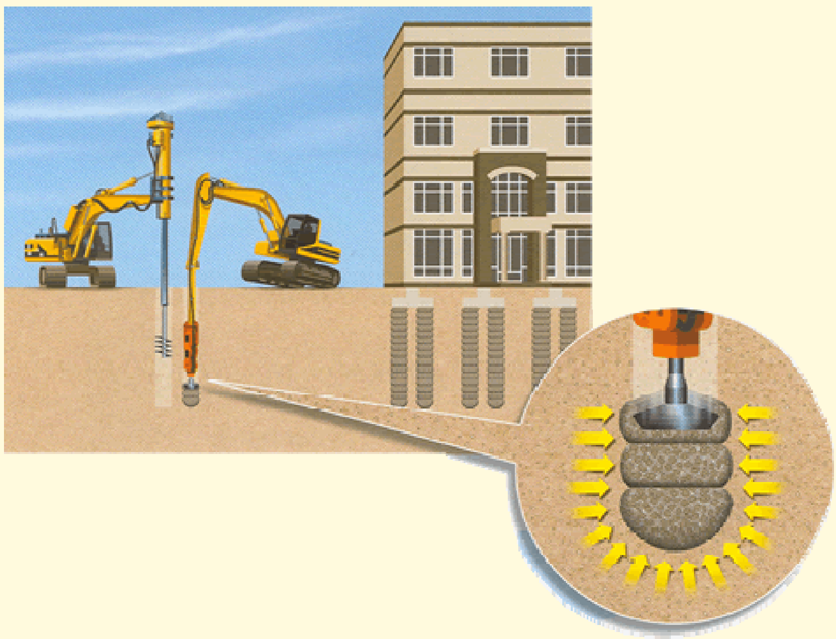
Surgery Space Redesign

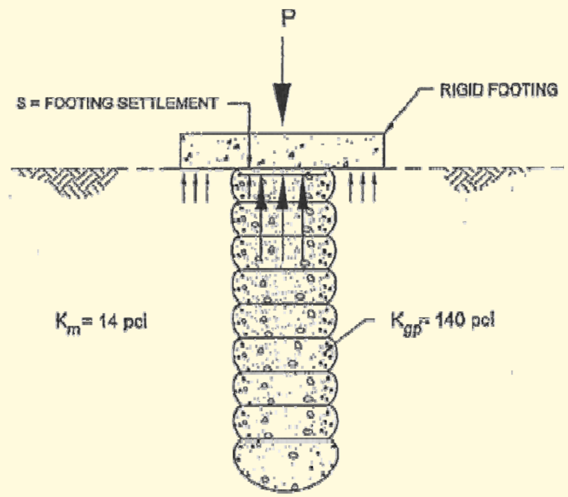
Vibration Design	
Mid-span Flexibility of Beam	6.7 E-06 in/lb
Mid-span Flexibility of Girder	1.7 E-06 in/lb
Mid-bay Flexibility	2.20 E-06 in/lb
Vibrational Frequency of Floor Slab	6.82 Hz
Max. Floor Displacement	186.3 µin
Vibrational Velocity of Floor	**7983** µin/sec **< 8000** µin/sec **OK**



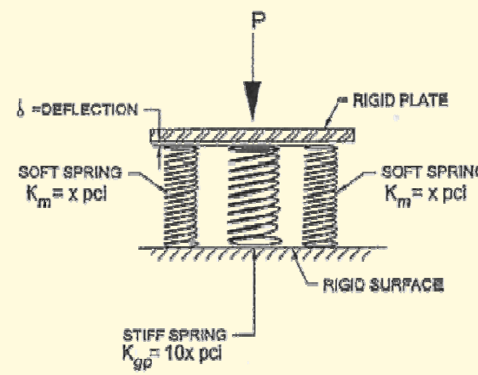
Foundation Redesign

- Geopier Intermediate Foundation System



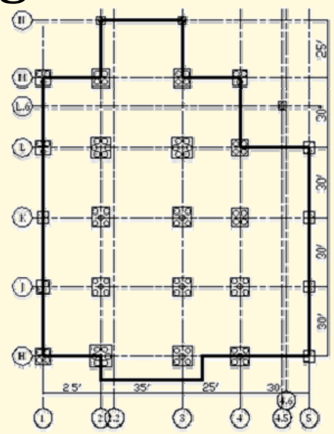


GEOPIER ELEMENTS AS "STRESS SINKS"

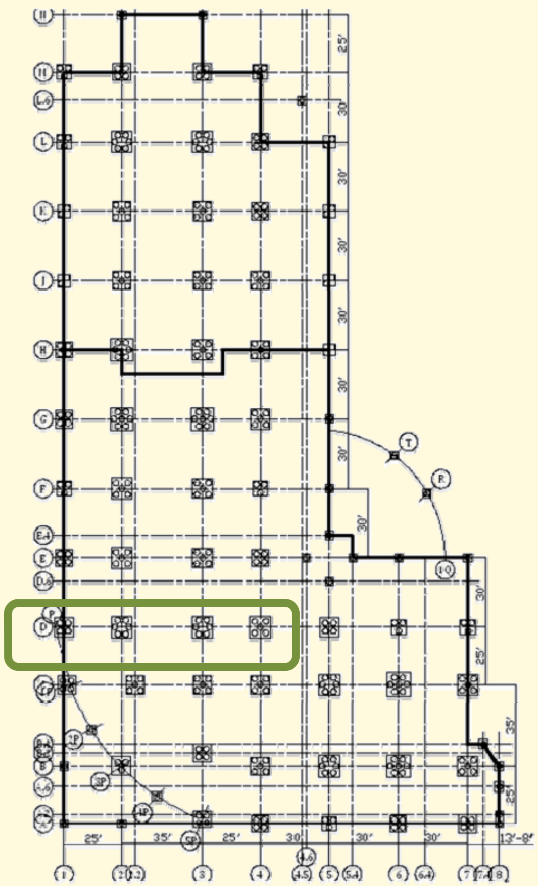


STIFF SPRING ANALOGY

Geopier Design

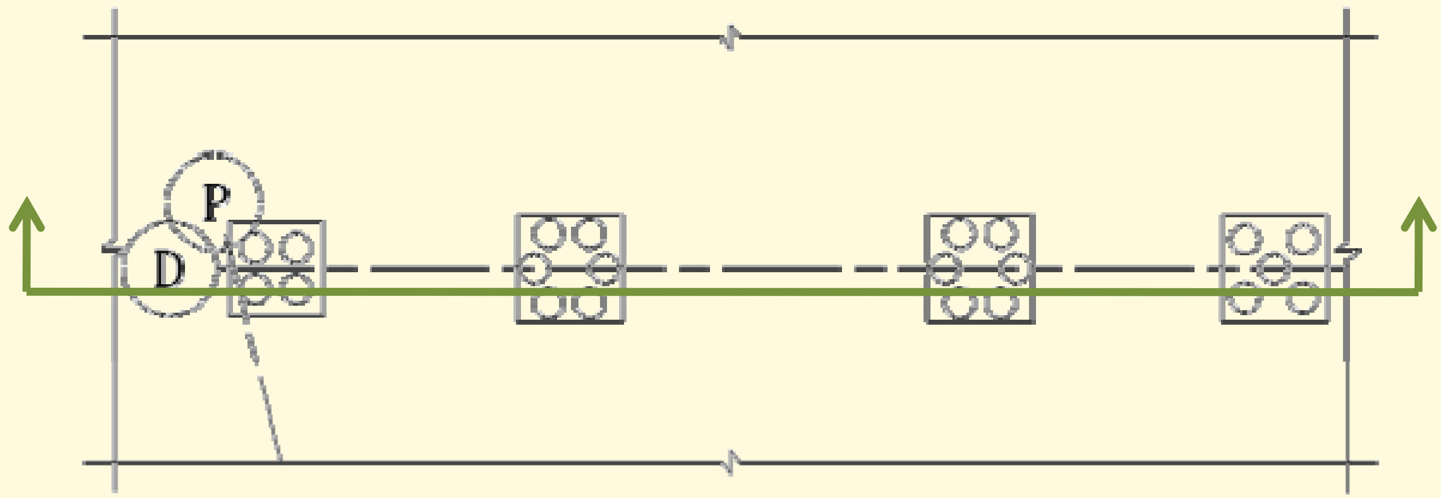


Basement Plan



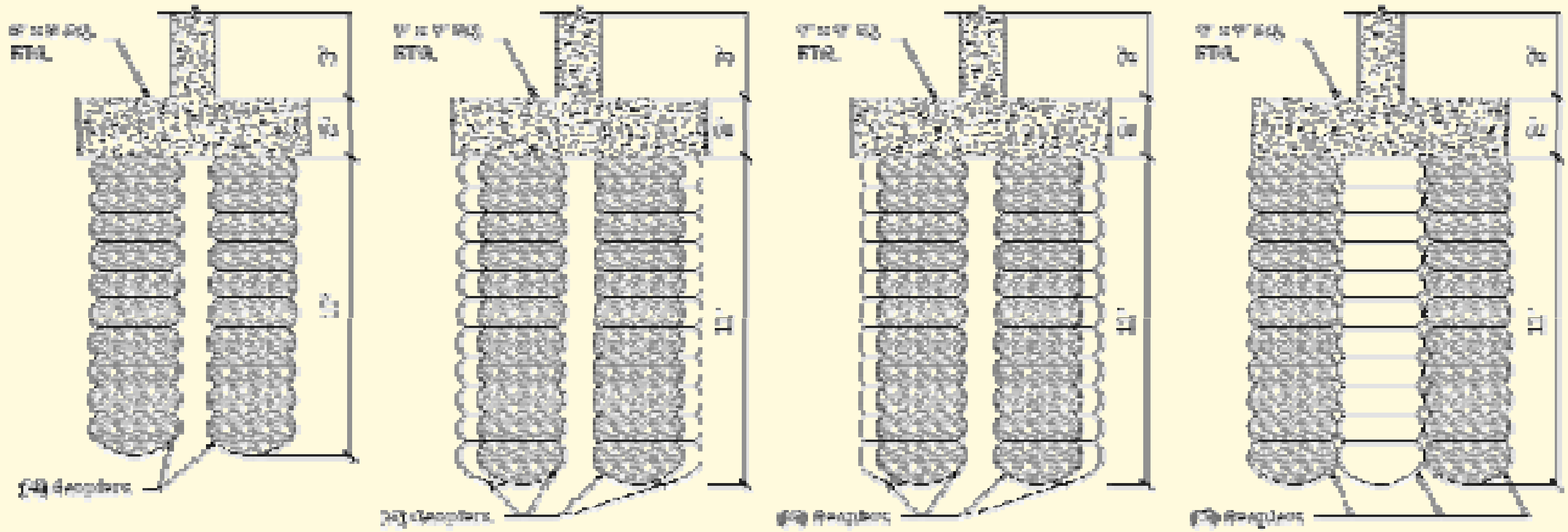
Foundation Plan

Geopier Design



Enlarged Plan View of Geopiers for SMF 3

Geopier Design



Section View of Geopier Elements for SMF 3

Presentation Outline

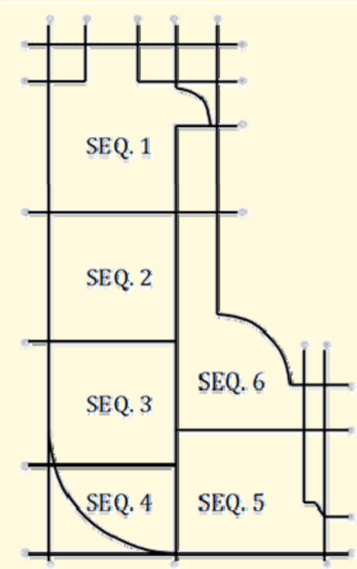
- Project Information
- Existing Structural System
- Problem Statement & Solution
- Structural Redesign
- Construction Management Study
- Recommendations

Construction Management

Component	Existing System (days)	Redesigned System (days)	Savings (days)
Foundations	92	44	+ 48
Structural Steel	119	88	+ 31
Connections	56	17	+ 39

Geopier system saves approximately 7 weeks!

SMF detailing saves approximately 4 weeks!



Sequencing Plan

Construction Management

Component	Existing System	Redesigned System	Savings
Foundations	$371,000	$190,000	+ $181,000
Structural Steel	$2,463,000	$1,871,000	+ $592,000
MF Connections	$269,000	$148,000	+ $121,000
Total	**$3,103,000**	**$2,209,000**	**+ $894,000**

	Existing System	Redesigned System
Cost	$3,103,000	$2,209,000
Cost/S.F.	$21.55	$15.34

Redesigned system saves $6.21/S.F. !

Presentation Outline

- Project Information
- Existing Structural System
- Problem Statement & Solution
- Structural Redesign
- Construction Management Study
- Recommendations

Recommendations

- SMF System
  - Reduction in number of moment frames
  - Reduction in tonnage of steel
  - Reduction in cost & construction time

Recommended ✓

- Surgery Space Redesign
  - Satisfies vibration criteria for "fast walking"

Recommended ✓

- Geopier Intermediate Foundation System
  - Provides vertical reinforcement to soil
  - Reduces cost & construction time

Recommended ✓

Acknowledgements

I would like to thank the following companies and individuals for their continuous support throughout the duration of my thesis project:

Ruby + Associates:
David Ruby
Jay Ruby
John Matuska
Allison Shenberger
David Walenga

The Pennsylvania State University:
Dr. Linda Hanagan
Dr. Andres Lepage
Dr. Louis Geschwindner
Professor Kevin Parfitt

Art Iron, Inc.:
Howard Shoenfeldt

Henry Gurtzweiler, Inc.:
Jim Momsen

Art Iron, Inc.:
Howard Shoenfeldt

Henry Gurtzweiler, Inc.:
Jim Momsen

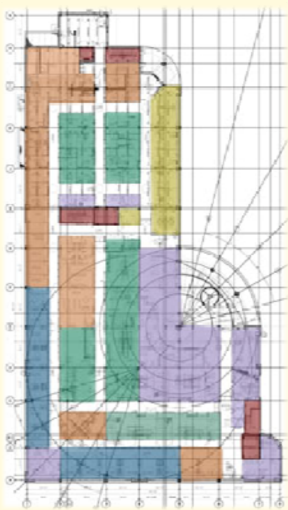
Friends & Family:
Parents
Penn State AE Class of 2009

Questions

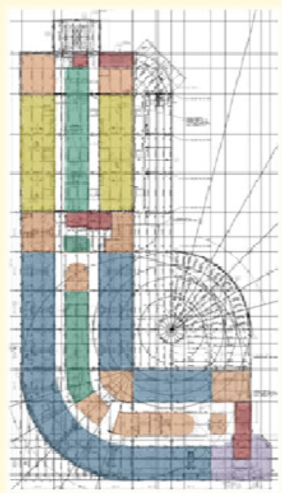
Building Architecture

- L-Shaped Footprint
- Patient rooms along perimeter
- Storage space located in center for easy accessibility

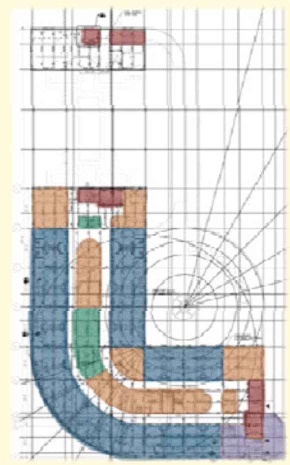
Patient Rooms
Administration
Lab/O.R. Space
Lobby Space
Storage
Stairs/Elevators



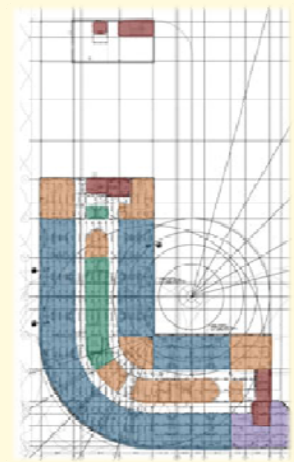
Main Floor



1st Floor

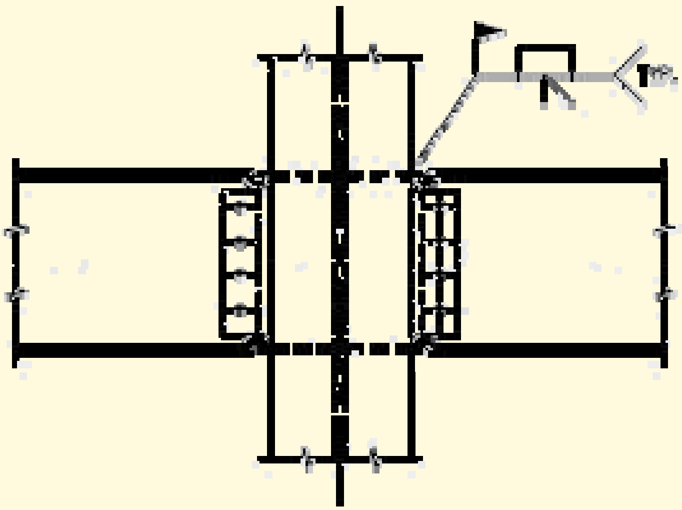


2nd Floor

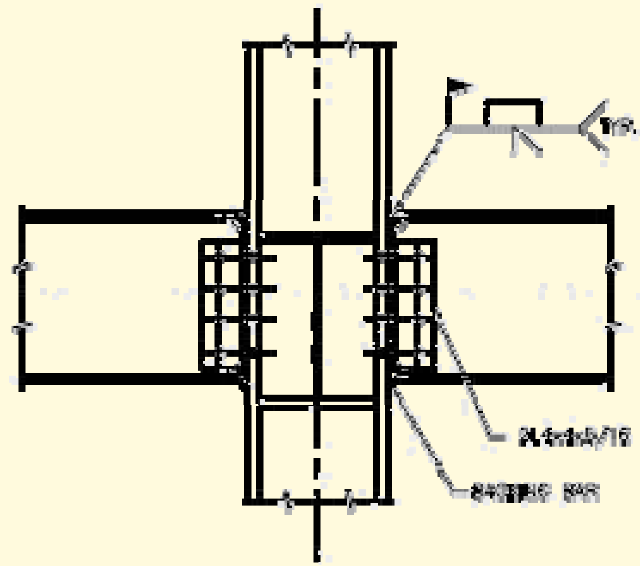


3rd Floor

Existing Moment Frame Connections



Weak-Axis Connection



Strong-Axis Connection

Design Basis

- ASCE 7-05
- FEMA-350 *Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings*
- FEMA-351 *Recommended Post Earthquake Evaluation and Repair Criteria for Welded Moment-Resisting Steel Frame Structures*
- AISC Seismic Design Manual

Wind Design Forces

Level	Wind Design					
	Load (k)		Shear (k)		Moment (ft-k)	
	N-S	E-W	N-S	E-W	N-S	E-W
Roof	42	28	0	0	2437	1580
3	82	53	42	28	3536	2287
2	78	50	125	81	2254	1450
1	76	48	202	131	1137	726
Total	**278**	**179**	**278**	**179**	**9364**	**6043**

Seismic Design Forces

Base Shear and Overturning Moment Distribution

Story	h_x (ft)	Story Weight (k)	$h_x{}^k W_x$	C_{vx}	$F_x = C_{vx}V$	V_x (k)	M_x (ft-k)
Roof	57.5	1093	97320	0.174	118	118	6790
3	43	2917	188250	0.337	228	347	14900
2	29	4074	169941	0.304	206	553	16029
1	15	5136	103204	0.185	125	678	10169
Main	0	6593	0	0.000	0	678	0
Total	57.5	19812	558715	1.000	678		47888
Base Shear =	**678**	**k**					

Torsion Effects

Torsional Moment Due to Seismic Loading

Story	North-South Torsional Moment				
	COM (ft)	COR (ft)	e_x (ft)	Story Force (k)	Torsional Moment (ft-k)
Roof	84.05	89.65	5.60	114	638
3	74.79	84.53	9.74	271	2640
2	67.77	79.30	11.53	208	2398
1	69.20	78.19	8.99	130	1169

Amplification Factor, A_o

Story	North-South Direction				
	δ_X (in)	δ_Z (in)	δ_{AVG} (in)	δ_{MAX} (in)	A_X
Roof	5.08	0.363	5.08	5.44	0.796
3	4.26	0.362	4.26	4.62	0.817
2	3.15	0.302	3.15	3.45	0.833
1	1.56	0.110	1.56	1.67	0.796

Torsion Effects

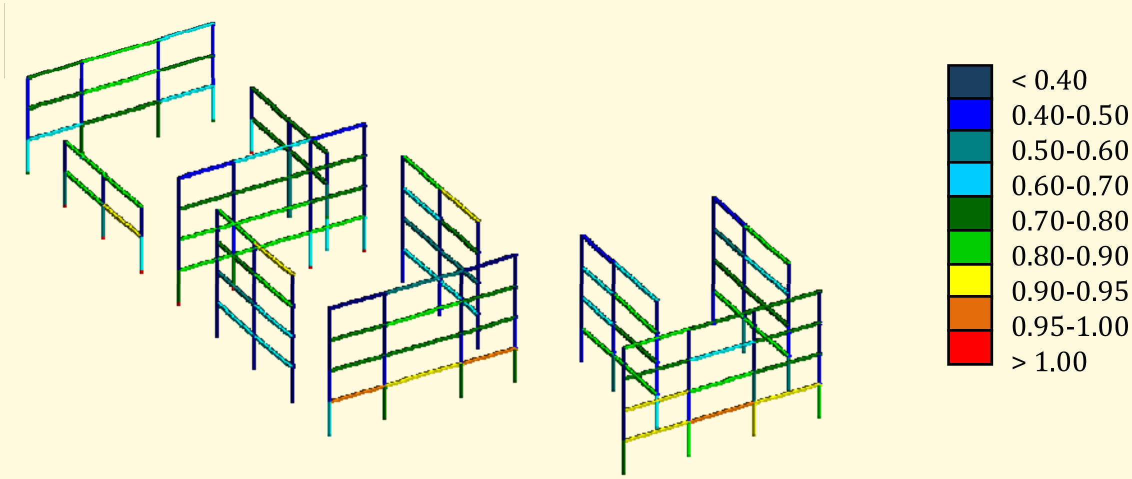
Torsional Moment Due to Seismic Loading

Story	East-West Torsional Moment				
	COM (ft)	COR (ft)	e_y (ft)	Story Force (k)	Torsional Moment (ft-k)
Roof	97.00	103.88	6.88	114	784
3	102.42	104.76	2.34	271	634
2	132.04	132.40	0.36	208	75
1	157.03	131.38	25.65	130	3335

Amplification Factor, A_o

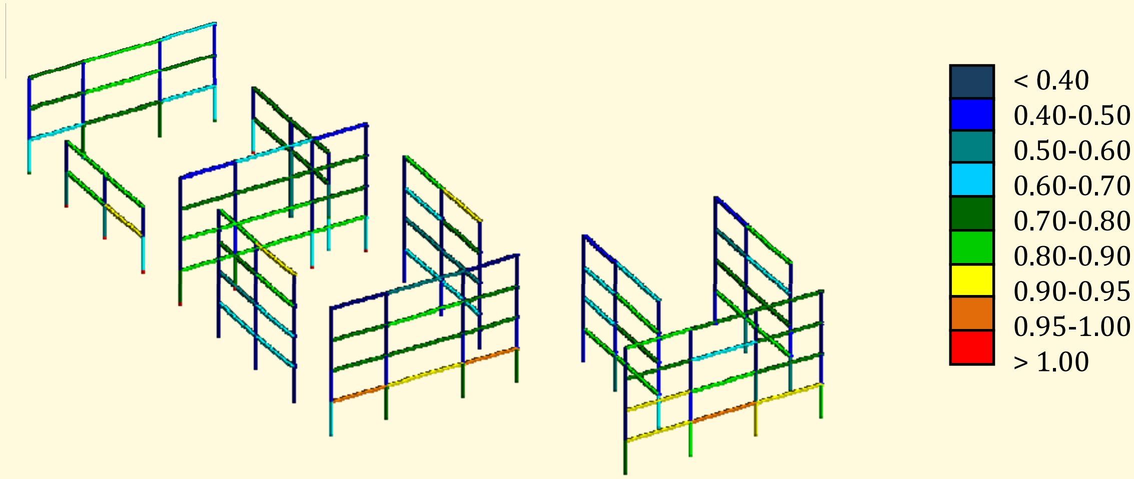
Story	East-West Direction				
	δ_X (in)	δ_Z (in)	δ_{AVG} (in)	δ_{MAX} (in)	A_X
Roof	4.66	0.030	4.66	4.69	0.703
3	3.90	0.114	3.90	4.01	0.734
2	2.86	0.120	2.86	2.98	0.754
1	1.42	0.122	1.42	1.54	0.817

Seismic Design Forces & Drift



Story	Total Drift (in)	Story Drift (in)	Amplified Drift (in)	Reduction $(C_u T_a)/T_x$		Allowable Story Drift (in)	
Roof	5.08	0.82	3.01	1.27	<	2.61	OK
3	4.26	1.12	4.09	1.73	<	2.52	OK
2	3.15	1.59	5.83	2.47	<	2.52	OK
1	1.56	1.56	5.70	2.42	<	2.70	OK

Seismic Design Forces & Drift



Story	Story Drift Ratio	0.7 x Story Drift Ratio	0.8 x Story Drift Ratio	Avg. Drift Ratio next 3 Stories	Soft Story Status
Roof	0.00471	0.00330	0.00377	--	No
3	0.00664	0.00465	0.00531	--	No
2	0.00946	0.00663	0.00757	--	No
1	0.00864	0.00605	0.00691	0.00694	No

Irregularities

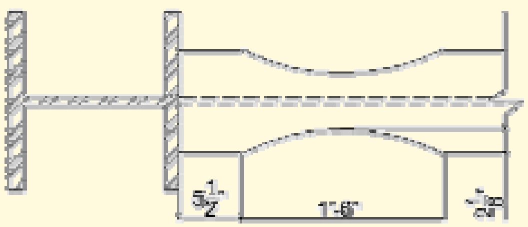
Horizontal Irregularities

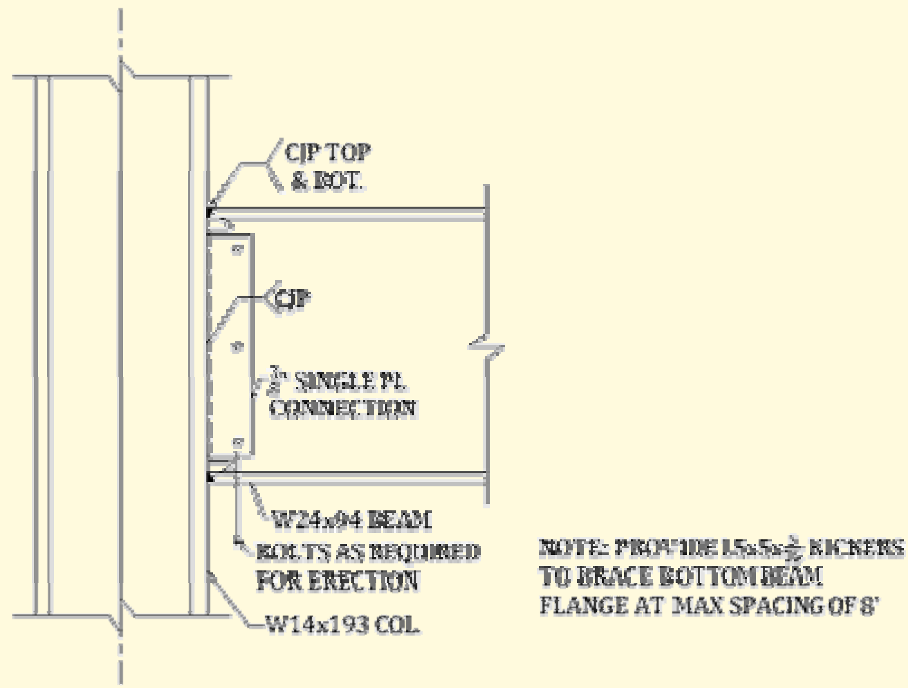
Irregularity Type	Comment	Status
Torsional	Upon completion of the RAM Model, irregularity does not exist. Please reference Appendix C for detailed calculations	OK
Re-entrant Corner	This irregularity does not apply to SDC C	OK
Diaphragm Discontinuity	By looking at the floor plans, irregularity does not exist	OK
Out-of-Plane Offsets	By looking at the floor plans, irregularity does not exist	OK
Non Parallel System	All lateral force resisting frames are parallel to the orthogonal grid	OK

Irregularities

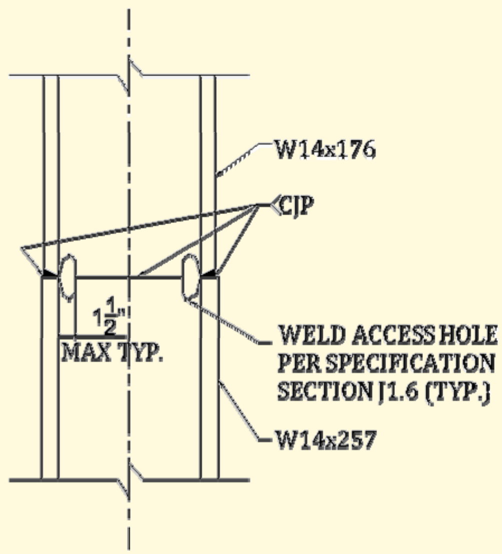
	Irregularity Type	Comment	Status
Vertical Irregularities	Stiffness-Soft Story	Upon completion of story drift check, irregularity does not exist (Reference Seismic Drift Section)	OK
	Weight Mass	Roof Wt./Adjacent Story Wt.= = 44psf/108 psf < 150% Reference Appendix A for story weights	OK
	Vertical Geometric	All SMF's are uniform throughout the entire height of the building	OK
	In-Plane Discontinuity of Vertical Lateral Force Resisting Element	By looking at the floor plans, irregularity does not exist	OK
	Discontinuity in Lateral Strength	Member sizes are increased going down the building, therefore there is higher strength at the lower floors	OK

RBS Connection Design- Exterior





RBS Connection Design- Column Splice



RBS Connection Selection Based on Economy

Steel Cost per Connection

Conn'x	Stiffening Requirement	Equiv. Wt. of Steel (lbs)	Column Wt. (lbs)	Total Wt. (lbs)	Tonnage	Cost ($/ton)	Total Cost
Alt. I	Stiffeners & Doubler	600	6963	7563	3.78	2250	$8505
Alt. II	Doubler	300	7689	7989	3.99	2250	$8978
Alt. III	None	-	8481	8481	4.24	2250	$9540

RBS Connection Selection Based on Economy

Fabrication & Installation Cost per Connection

Configuration	Total Fabrication (hrs)	Cost ($/Fab. Hr)	Installation (hrs)	Cost ($/Man hr)	Total Cost
Alternative I	7.7	45.00	30.5	70.00	$2,482
Alternative II	6.2	45.00	19.5	70.00	$1,644
Alternative III	4.8	45.00	9	70.00	$846
Existing	2.4	45.00	4.5	70.00	$423

SMF Design Conclusions

Lateral + Gravity	Tonnage of Steel	Density of Steel (psf)
Existing System	894	11.69
Redesigned System	678	8.80