95 State Tower Performance-Based Seismic Design Using PEER TBI Guidelines

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PEER

2023 PEER Annual Meeting
MLK Building, U.C. Berkeley
August 24, 2023

SOM

95 State at City Creek
Salt Lake City, UT

Introduction

- Commercial Office Tower + Religious Center
- 26 stories, 395 ft., 621,628 gsf
- Alternate procedures using PEER TBI v.2.03 guidelines

Key issues

1. PBD permits more reliable seismic performance

2. Nonlinear analysis and design informs the design process

3. PEER TBI PBD guidelines and procedures

95 State at City Creek

Alternate Procedure by 2015 IBC Section 104.11

Petition Salt Lake City Corporation (AHJ)

- Request to use 2015 IBC “Alternate Procedure” per Section 104.11
- Core wall lateral structural system (395-ft) exceeding 240-ft as permitted by ASCE 7-10 Sec. 12.2.5.4
- Seismic Design Category: D
- Seismic Risk Category: III, I_e = 1.25

Equivalent Seismic Performance per Section 104.11

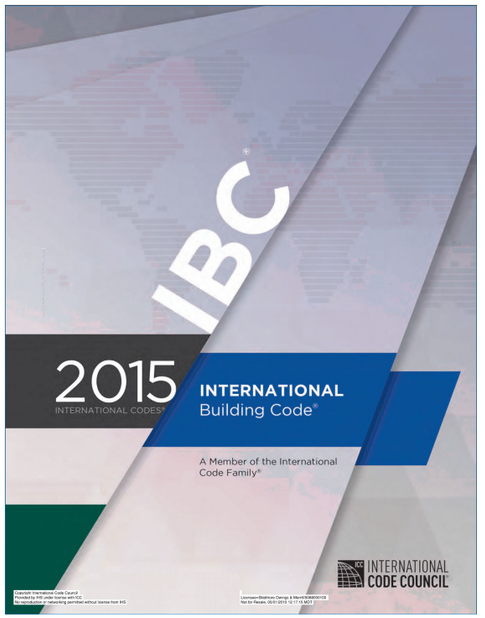
- *“The alternate building design procedures … are intended to achieve not less than the equivalent seismic performance of that prescribed by 2015 IBC provisions in quality, strength, effectiveness, fire resistance, durability and safety.”*

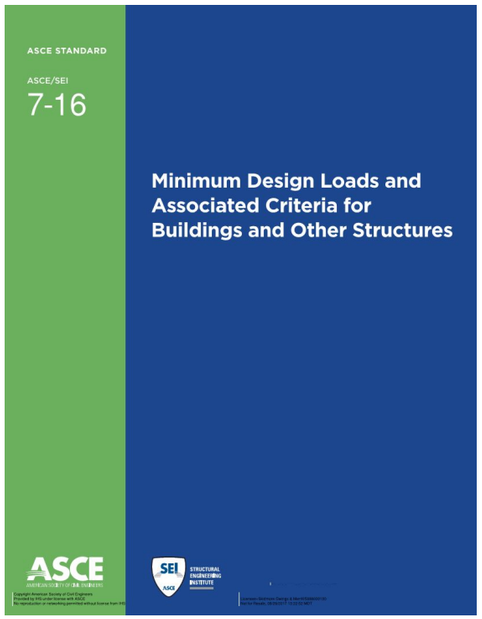
Adopted Structural Design Codes and Standards

- ASCE 7-16, PEER TBI v.2.03 (2017) Sec. 1.3
- AISC 360-16, AISC 341-16, AISC 358-16, ACI 318-14, ASCE 41-17, ATC 72-1, NIST Technical Notes

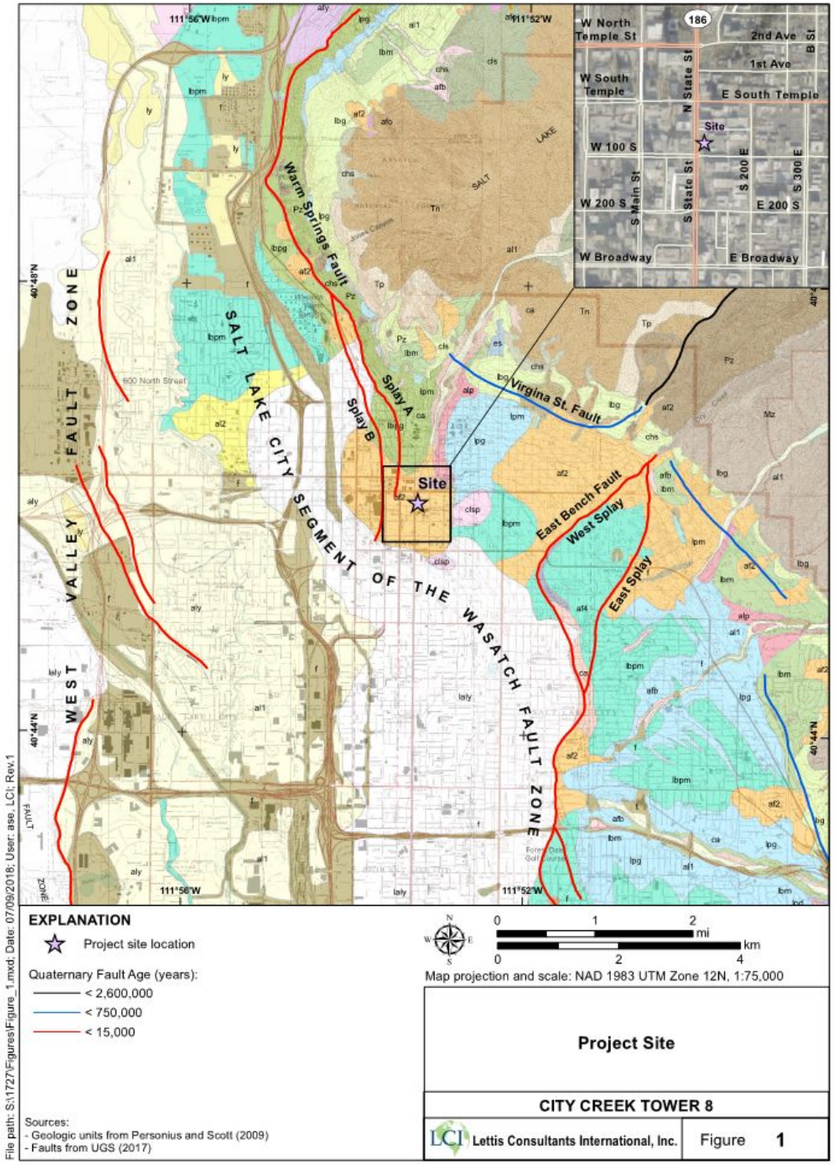
Independent Peer Review Panel

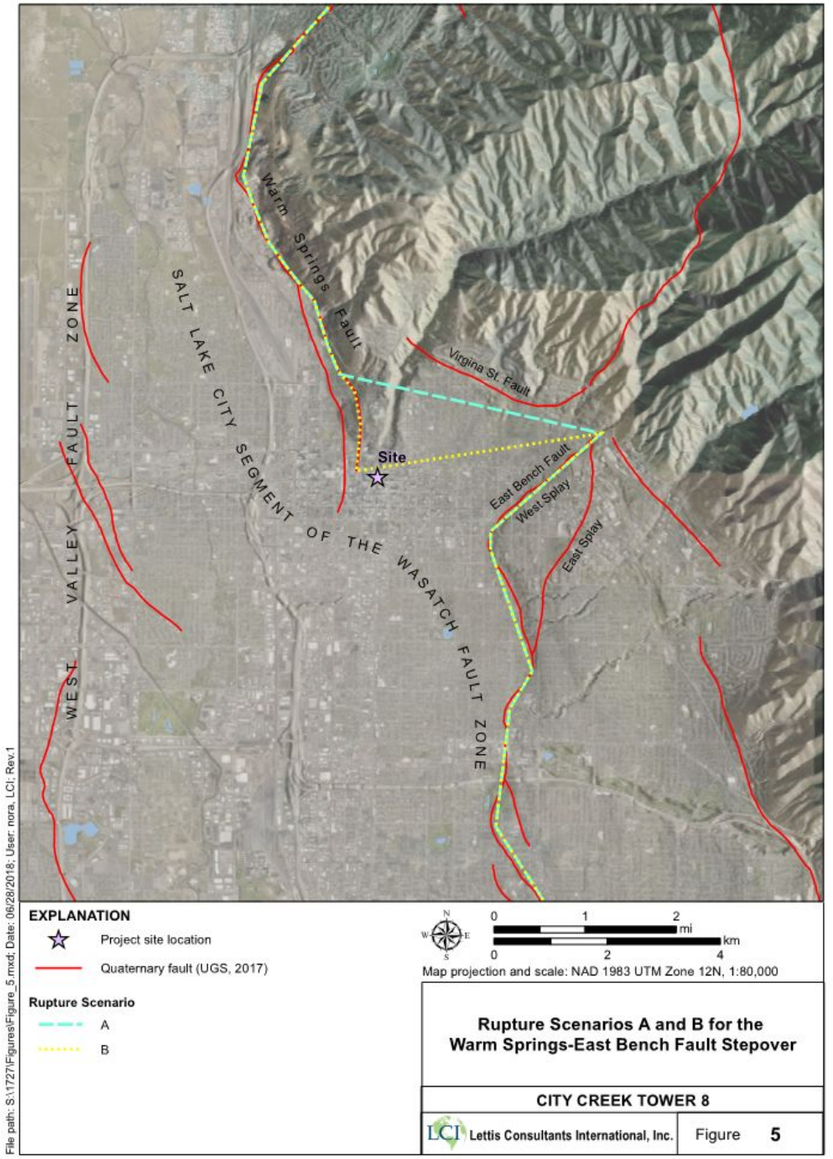
- Chris Kimball, Chair, SE at AHJ; Maffei SE - Joe Maffei, Noelle Yuen, Karl Telleen, Saeed Fathali
- Seismic hazards and ground motions - Norm Abrahamson



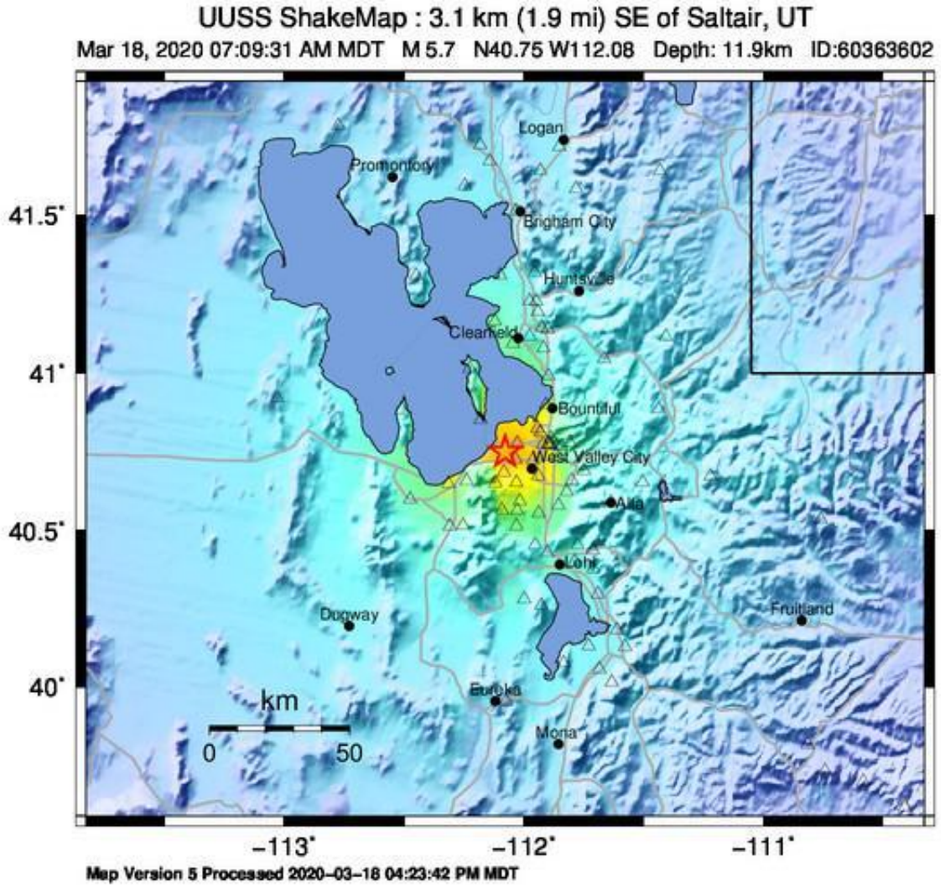


Regional Seismicity



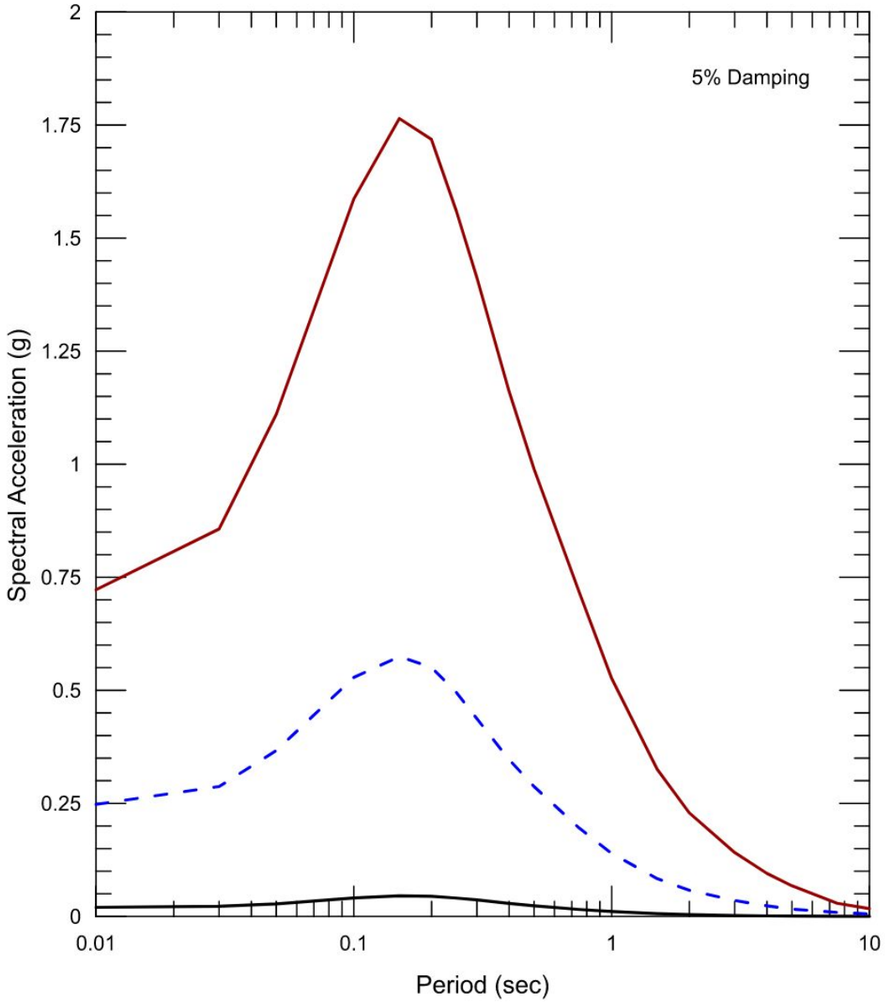


Site-Specific Seismic Hazard & Ground Motions



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*0.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999



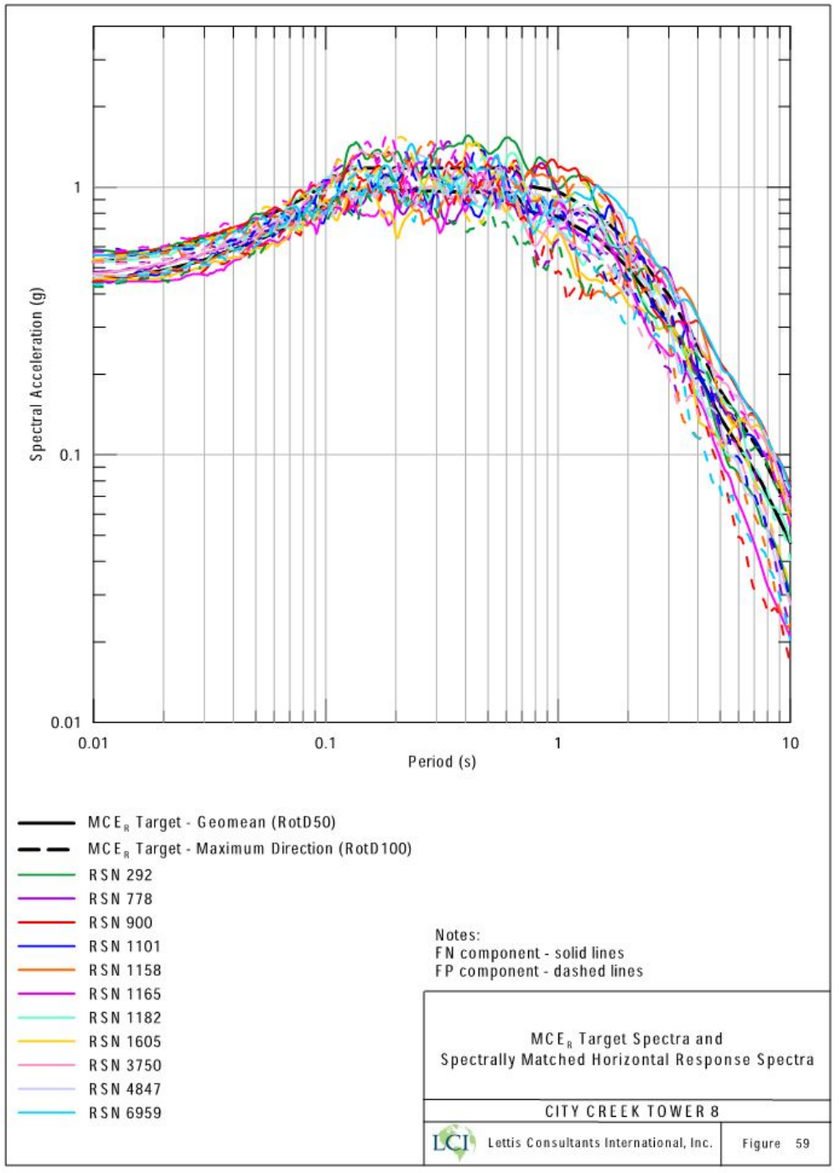
Return Period (Years)
- 43
- 475
- 2475

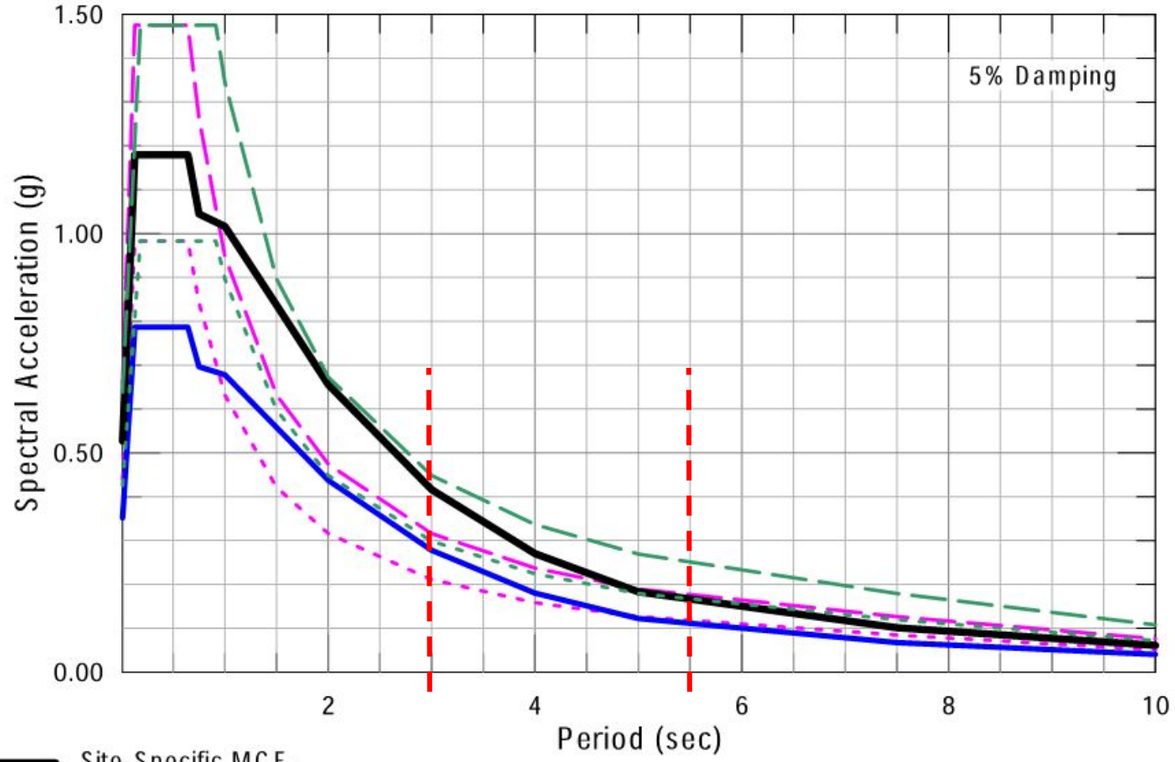
5%-Damped Uniform Hazard Spectra for V_S30 760 m/sec

CITY CREEK TOWER 8

Lettis Consultants International, Inc. | Figure 32

Site-Specific Seismic Hazard & Ground Motions





Site-Specific MCE$_R$

Site-Specific DE

ASCE 7-16 MCE$_R$, Site Class D
(Fa=1.0,Fv =1.762)

ASCE 7-16 DE, Site Class D
(Fa=1.0,Fv =1.762)

ASCE 7-16 MCE$_R$, Site Class D
(Fa=1.0,Fv =2.5)

ASCE 7-16 DE, Site Class D
(Fa=1.0,Fv =2.5)

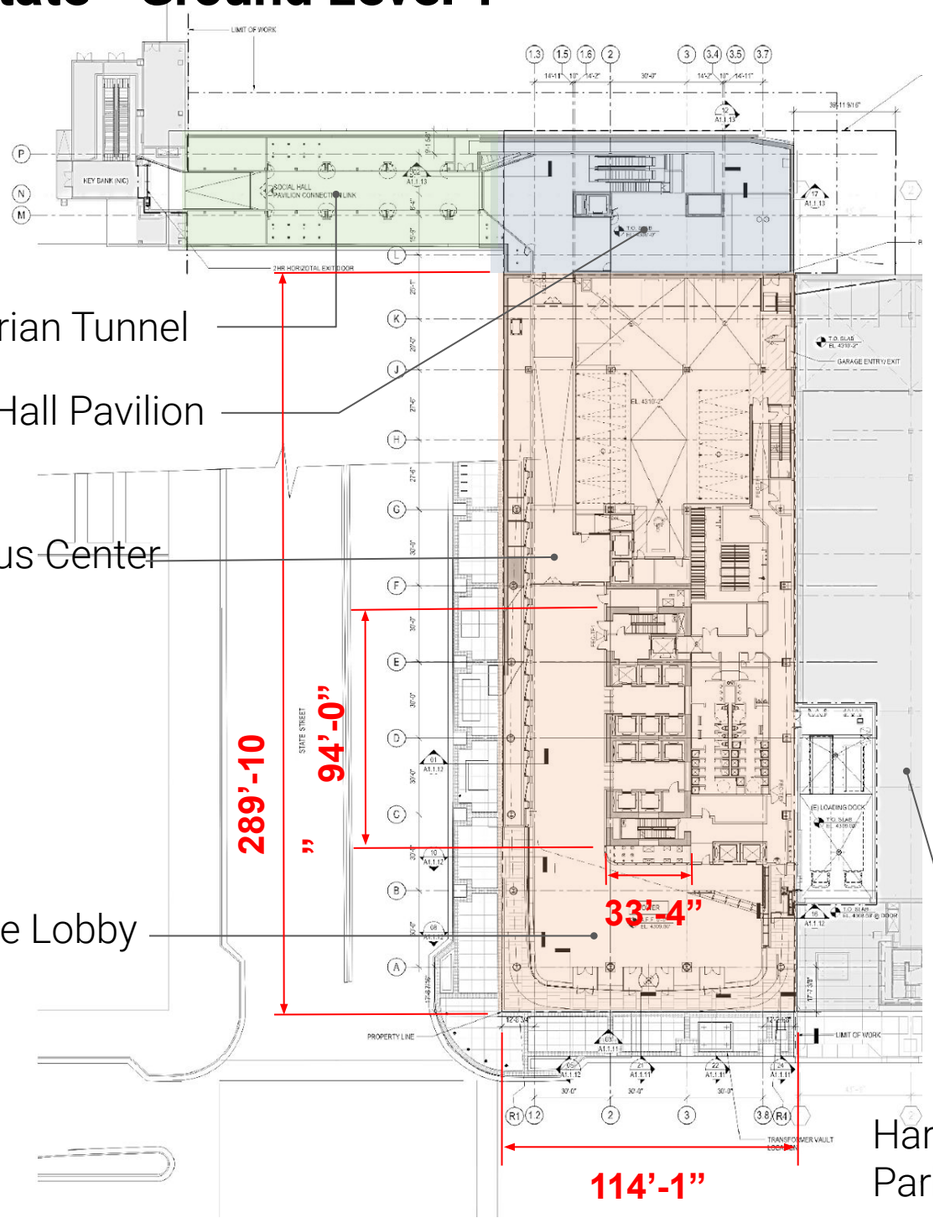
MCE$_R$ 1,930 - 1,975 ARP
(2.5% to 2.6% in 50 yrs)

Site-Specific Horizontal MCE$_R$ and DE Spectra
Compared to ASCE 7-16 Code Spectra
for Site Class D

CITY CREEK TOWER 8

LCI Lettis Consultants International, Inc. | Figure 48

95 State - Ground Level 1



Tower & Podium Structural Systems

Superstructure Gravity System

- Conventional WF steel column and composite steel metal deck slab framing
- Level 1 cast-in-place reinforced concrete
- 1 to 2 story basement Level

Superstructure Seismic Force-Resisting System

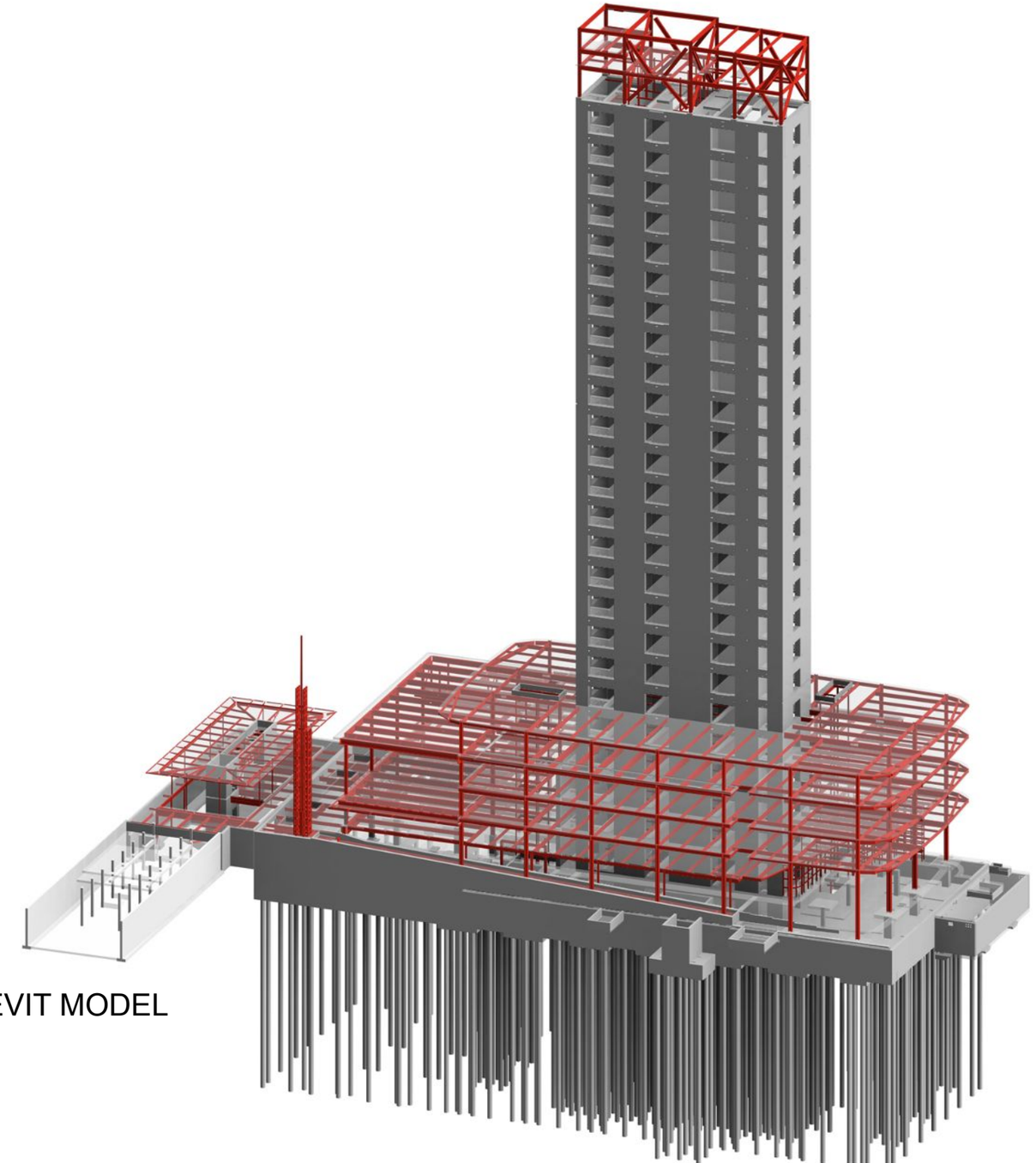
- Special reinforced concrete shear walls and ductile coupling beams, 24” to 30” thick, f'_c = 8,000 psi
- R/C Level 1 transfer diaphragm and perimeter walls
- Steel composite floor diaphragms

Roof Mechanical Penthouse

- Steel ductile eccentric braced frame (EBF) + OMF
- System strength and deformation capacity of EBF

Deep Pile Foundations

- Auger cast-in-place piles (363 @ 24” dia.) to depth of ACIP (110 ft.)
- 11 ft. deep tower foundation mat
- Transverse direction 6 ft. to 11 ft. grade beam outriggers



3D REVIT MODEL

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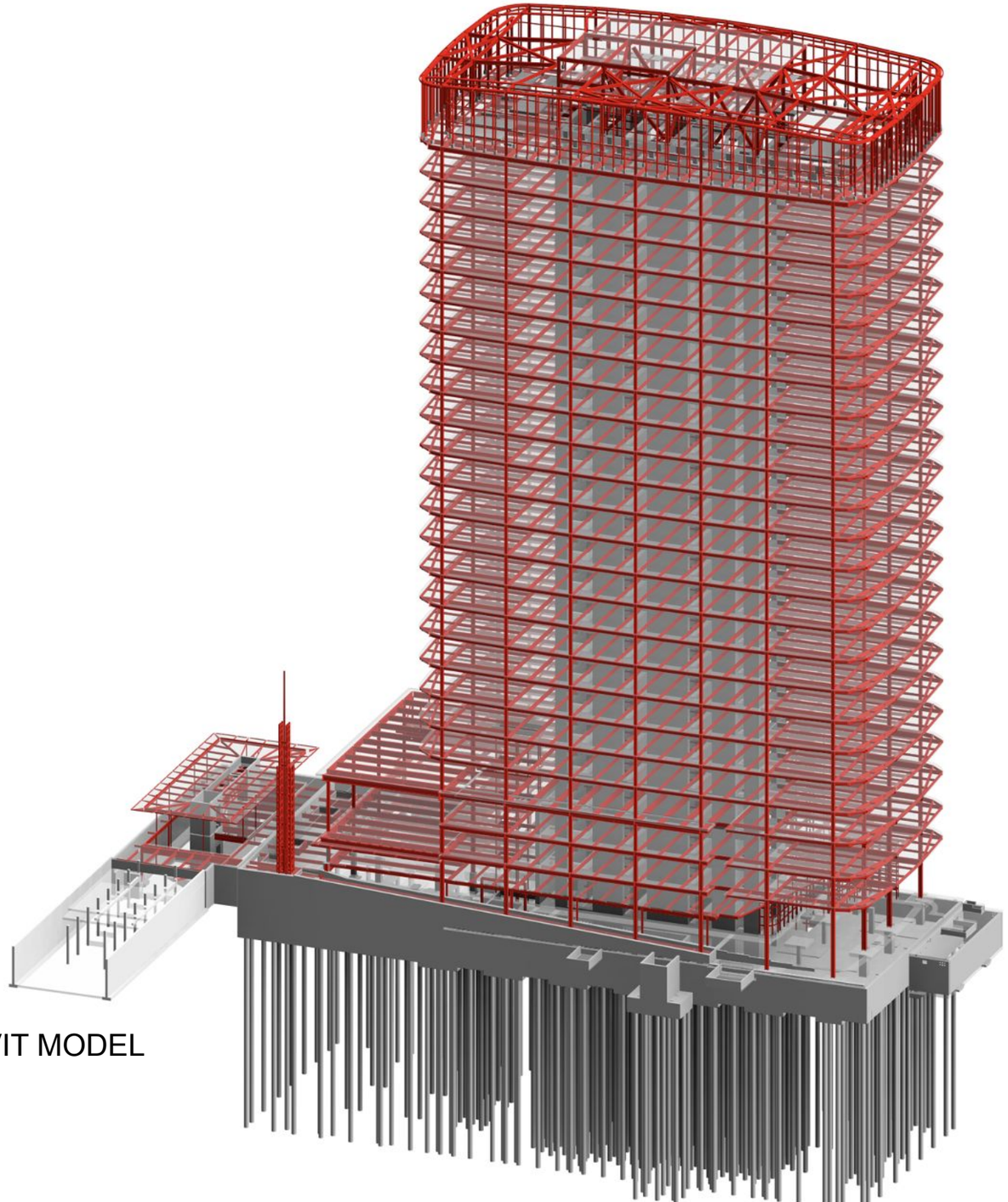
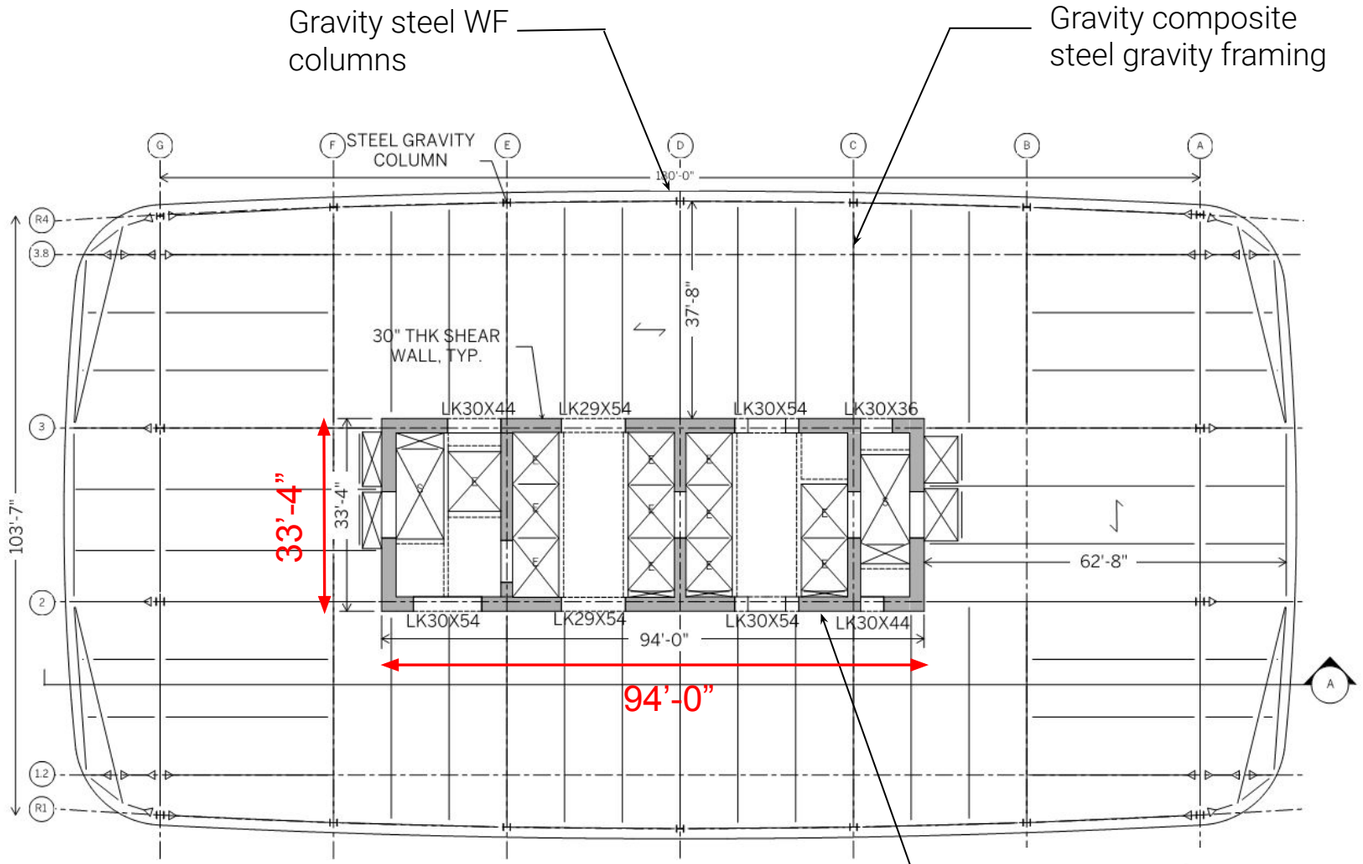


3D REVIT MODEL

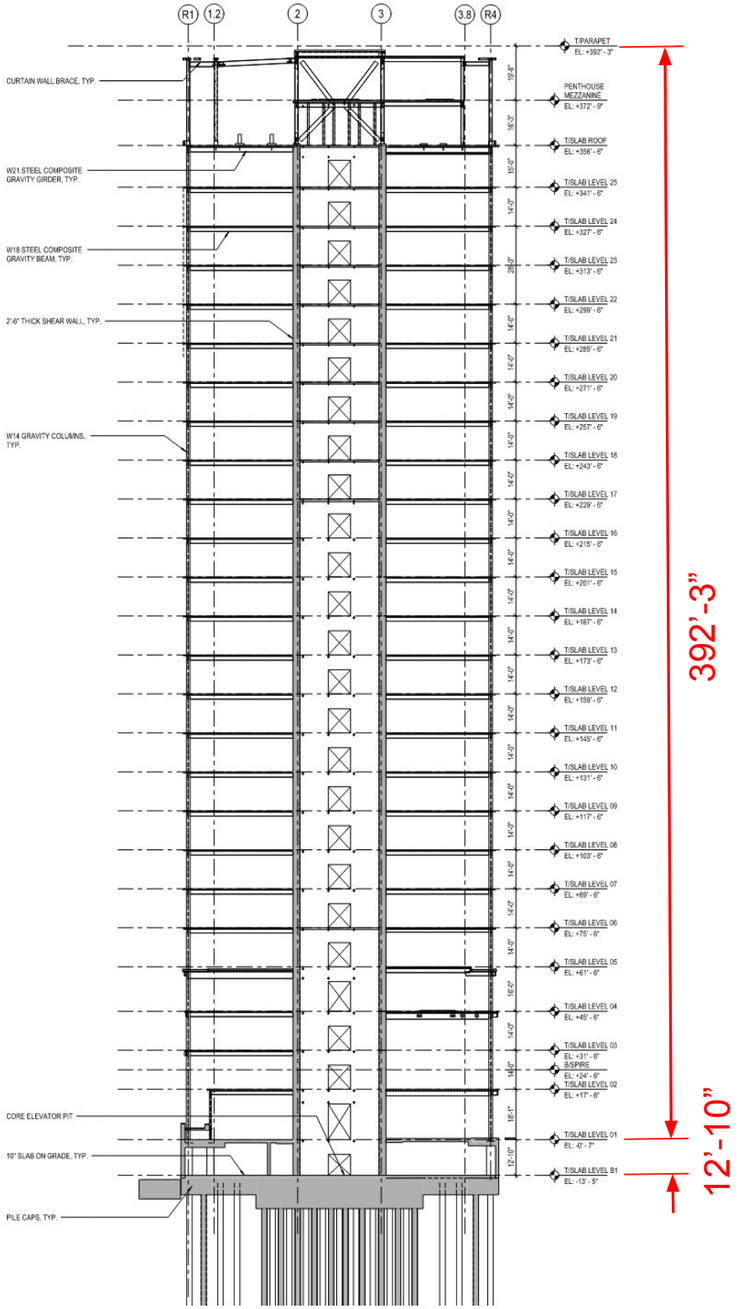
Structural Systems

Typical Tower Framing Plan



Typical Framing Plan

Transverse core aspect ratio = 392'-3"/ 33'-4"= 11.8



Core Wall Transverse East-West Section


100% PPE
AT ALL TIMES


100% PPE
AT ALL TIMES

Detailed Structural Design Criteria

Non-prescriptive Seismic Design Procedures

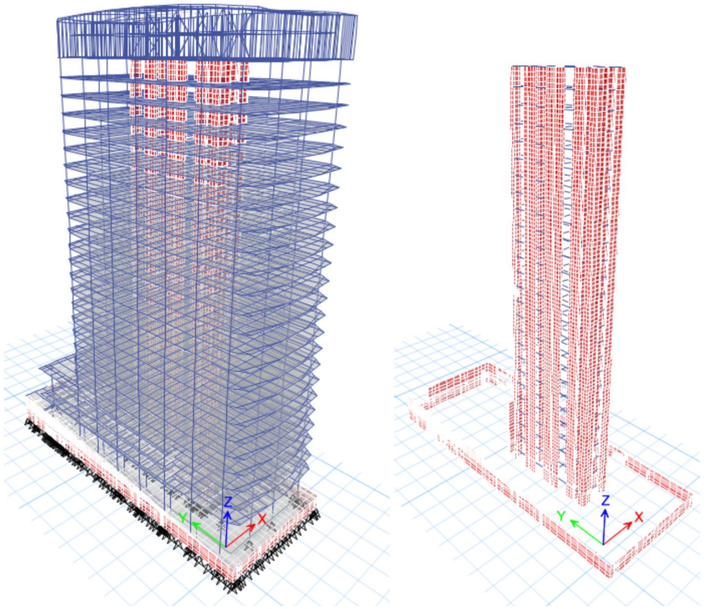
Analysis and Design Approach

1. **Linear Elastic Code Equivalent Level Evaluation**
   - MCE_R MRSA (R=3.5, 2.0, 2.5), 5.0% damping
   - Global Deformation and force controlled elements
   - Diaphragms, foundation pile cap, connections and piles

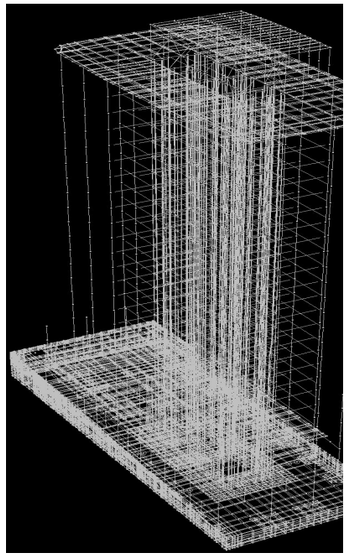
2. **Service Level Earthquake (SLE) Evaluation**
   - MRSA Essentially elastic response with post-event occupancy
   - 43-yr PSHA (50%, 30yrs), 1.8% damping (TBI Eq 4-1)

3. **Risk-targeted Maximum Considered (MCE_R) Evaluation**
   - MCE_R nonlinear response history analysis, 2.5% damping, I_e = 1.25
   - Global story drift and residual drift limits
   - Deformation and force controlled element acceptance criteria
   - Bounded backstay, transfer diaphragm and basement walls
   - PEER TBI / ASCE 7-16 MCE_R Performance Objectives
     - Low probability of building collapse
     - Low probability large residual drift
     - Low probability cladding will fall

4. **Peer Review Panel Comment / Response**
   - Detailed global and component investigations
   - Prescriptive DE level design code checks



Linear CSI ETABS
v16.2.1 (2016)

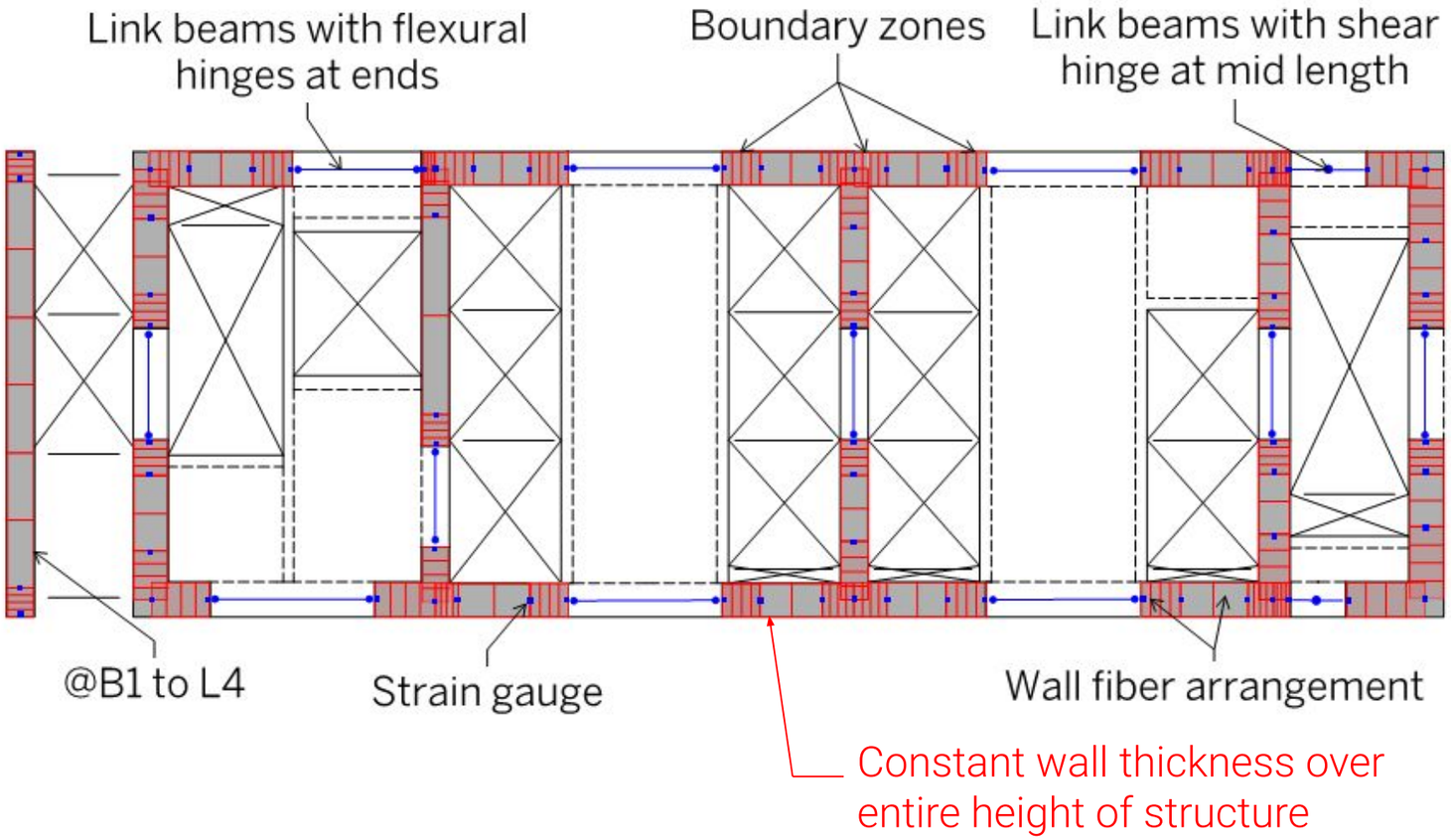


Nonlinear CSI
Perform 3D v7.0.0

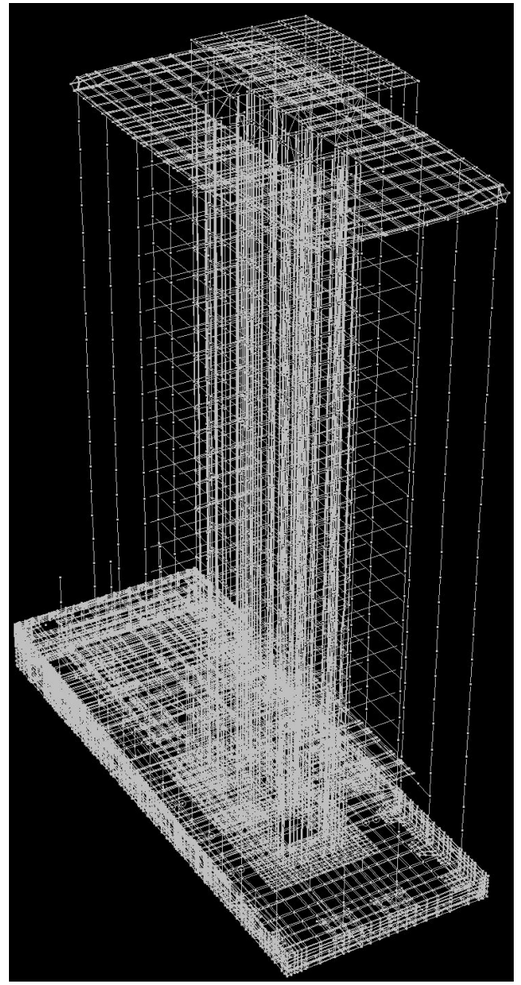
= mean * 1.3 * Ie (1.25)
RC III

Nonlinear Analysis and Design

Core Wall and Coupling Beam Nonlinear Modeling



Modeling of Nonlinear Elements



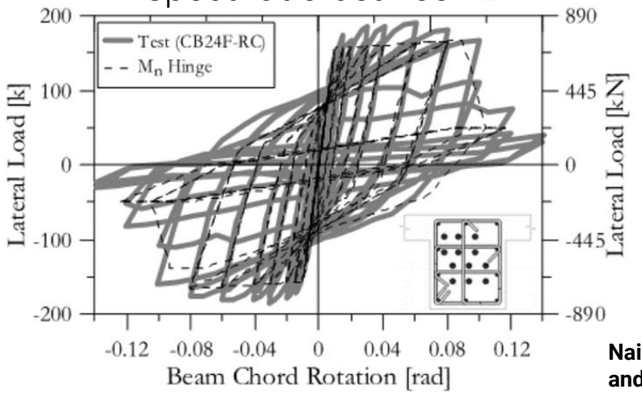
CSI Perform 3D v7.0.0

Nonlinear Analysis and Design

Nonlinear Coupling Beam Modeling

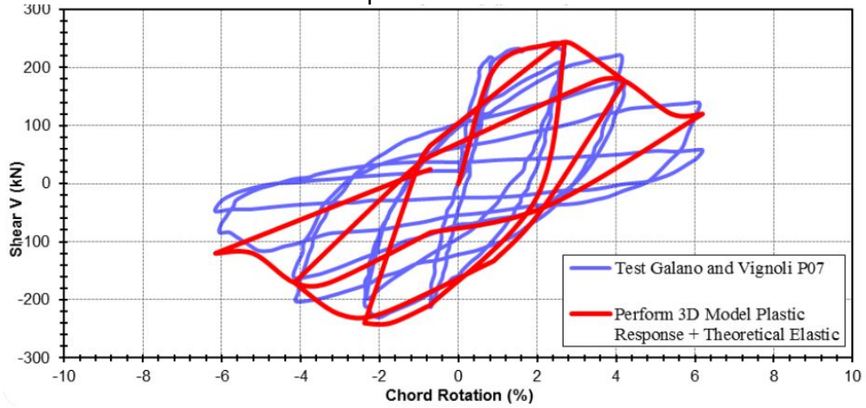
Coupling Beam Parameter Verification Based On Historic Test Data

Aspect ratio between 2-4



Naish, Wallace, Fry, and Klemencic (2010)

Aspect ratio ≈1.5



Galano and Vignoli (2000)

- *Naish, Wallace, Fry, and Klemencic (2010) Modeling of diagonally reinforced concrete coupling beams*
- *Galano and Vignoli (2000) Seismic behavior of short beams with different reinforcement layouts*

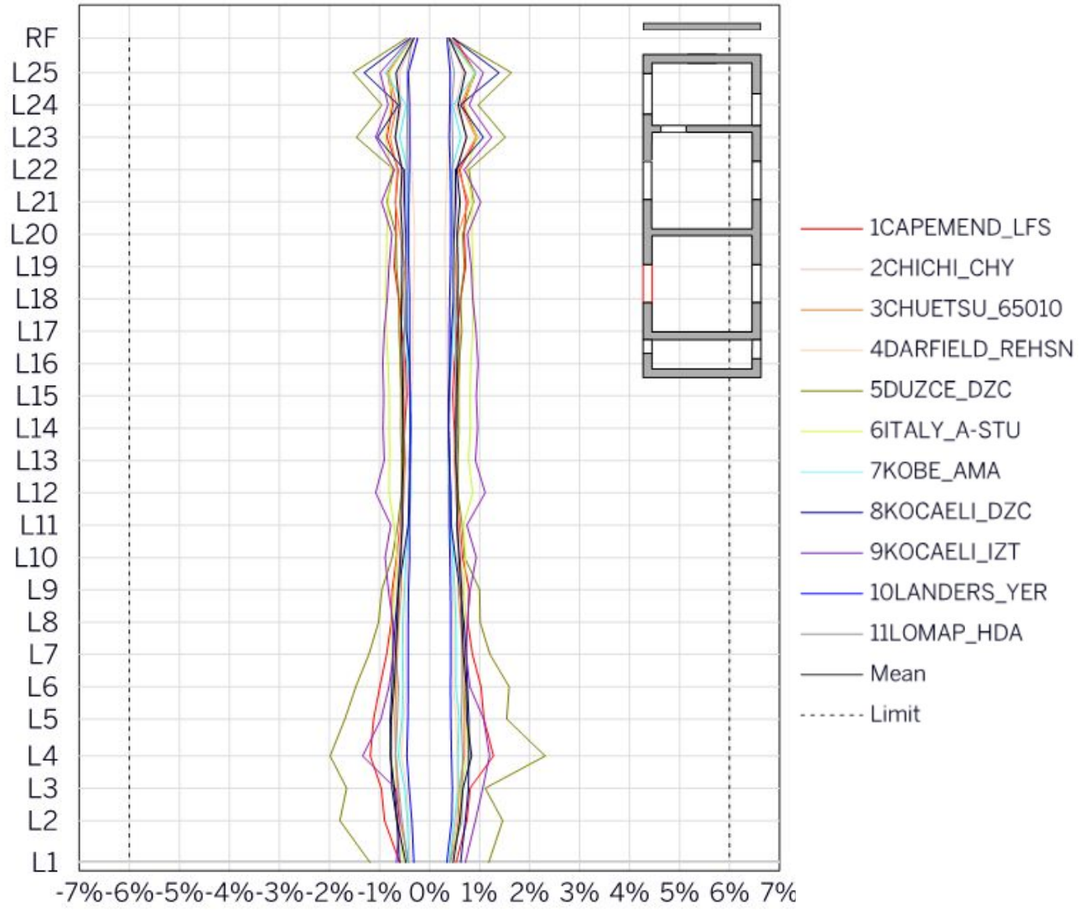
Coupling beam parameter input in Perform 3D

Coupling beam type	Diagonally reinforced	
l_n/h =	1.50	
Cross Section		
Basic Info	Type **(e.g. Beam, Reinf. Conc. Section)**	Beam, Reinf. Conc. Section
	Name in model	XecBmC-LK24X64-C8-SH-0.15Ig-0.5Av
Shape and Dimensions	Section Shape **(e.g. rectangle)**	Rectangle
	B (width, in)	24
	D (depth, in)	64
Section Stiffness	I_g^* = 0.15*b*h^3/12	78643.2
	A_v^{TT} = 0.5*0.83*b*h	640
Calculated yield rotation		
Flexural*:	$\theta_{ym} = M_{ne}*L/(6EI)$	0.00205
Shear*:	$\theta_{yv} = 2*M_{ne}/(GA_vL)$	0.00024
Total:	$\theta_{ym} + \theta_{yv}$	*0.00229*
Material Stiffness	E **(100% of gross)** (ksi)	5813
	ν	0.2
	G **(100% of gross)** (ksi)	2422
Inelastic Component		
Basic Info	Type **(e.g. FEMA beam)**	Shear Hinge, Displacement Type
	Name in model	CpdLKBM-SH-8KSI_LK24X64-1-L96
	Shape of Relationship **(e.g. Trilinear)**	Trilinear
	Symmetry **(Y/N)**	Y
	Strength Loss **(Y/N)**	Y
	Upper/Lower Bounds (Y/N)	N
	Use Cross Section **(Y/N)**	Y
	Deformation Capacities **(Y/N)**	Y
	Cyclic Degradation Type **(e.g. YULRX)**	YULRX
Basic F-D Relationship	Beam Clear Length (in)	96
	FY (yield strength, kips)	853
	FY/ Vn,expected **(e.g. 0.9)**	1
	FU (ultimate strength, kips)	1040
	FU/ Vn,expected **(e.g. 1.33)**	1.22
	DU (in)	1.344
	DX (in)	19.2
	KH/KO	*calculated by Perform*
Strength Loss	DL (in)	2.4
	DR (in)	4.32
	FR/FU	0.001
	Strength Loss Interaction	0.25

Beam span-to-depth (L/H) ratios range: 0.89 to 2.63
Diagonally reinforced coupling beams

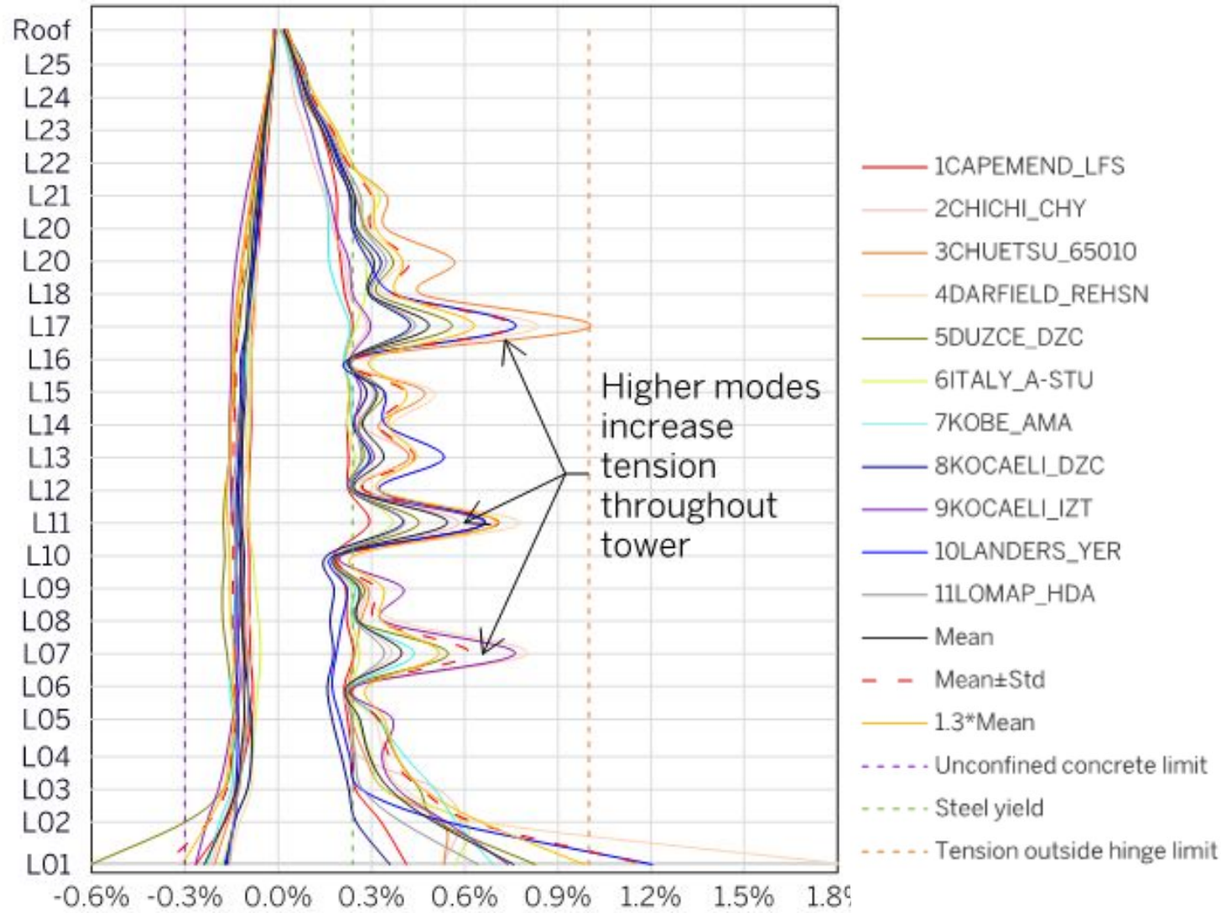
Nonlinear Analysis and Design

NLRHA Evaluation of Stage 1 Linear Analysis and Design



Coupling Beam Rotation

- Low ductility and beam energy dissipation



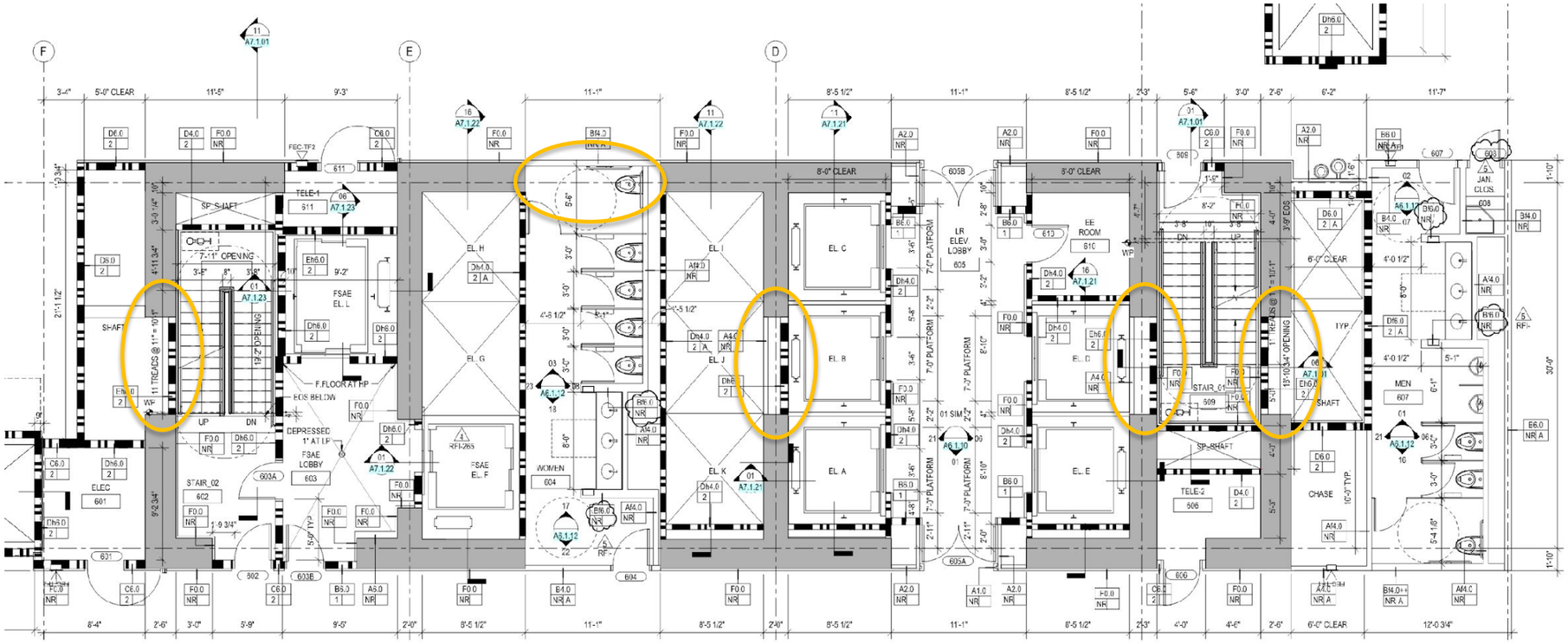
Wall Fiber Strain (%)

- Wall yielding steel tension strains over height
- Large tension and compression strains at base

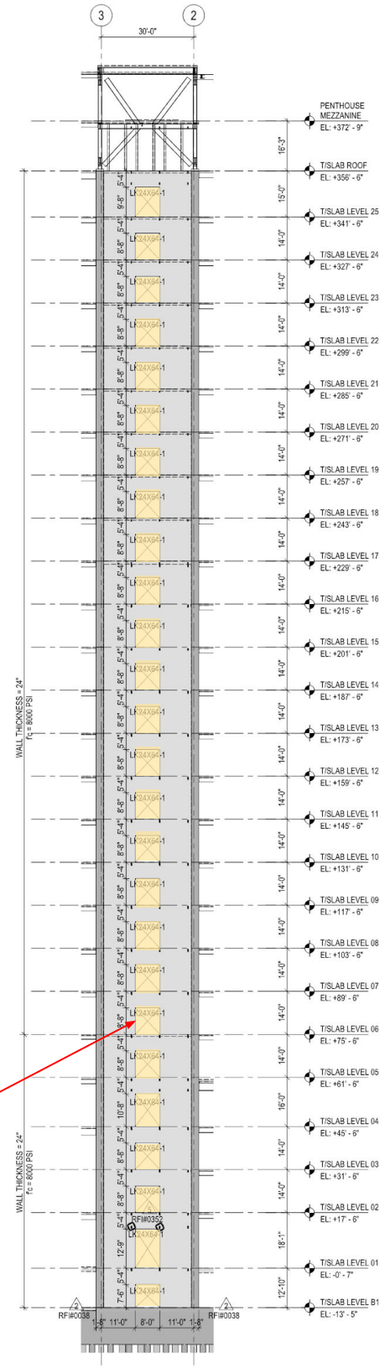
Designed using linear analysis procedures

Nonlinear Analysis and Design

Increased Coupling Beam Ductility and Energy Dissipation



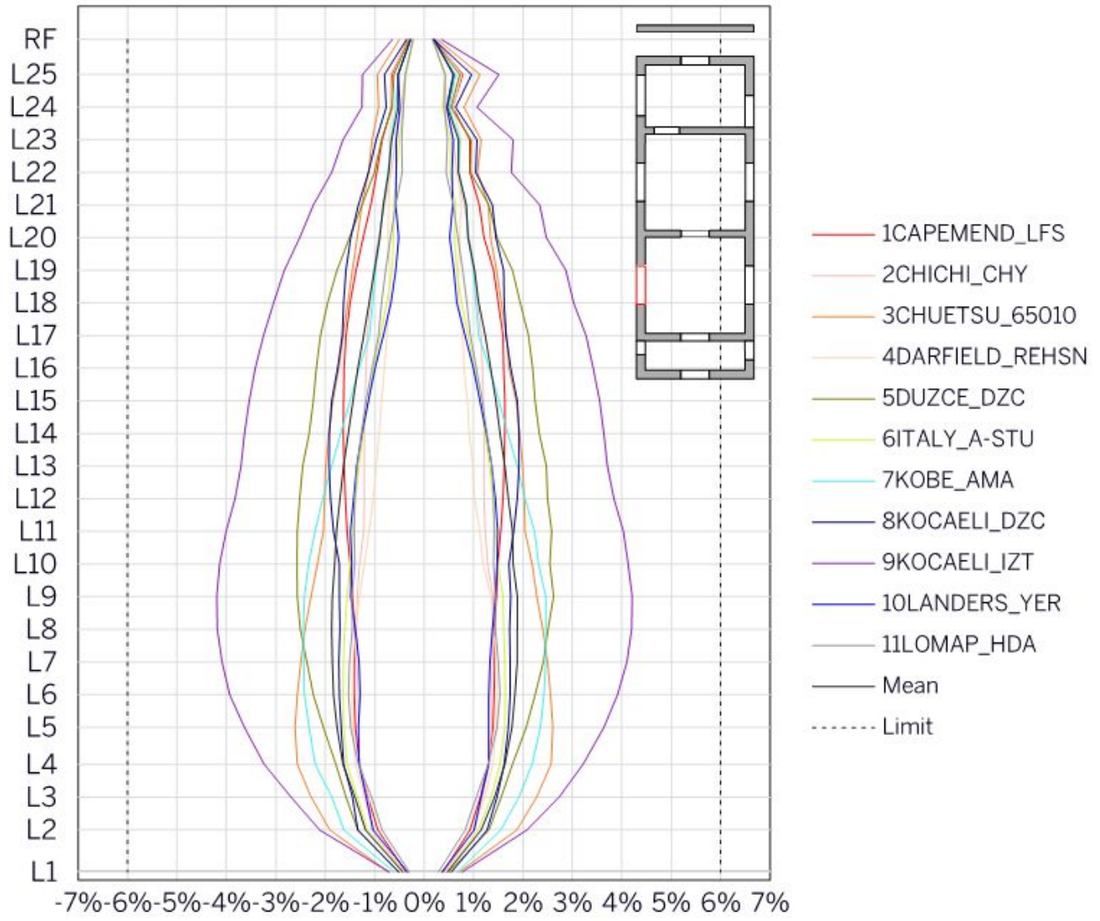
Modeling of Nonlinear Components



Added wall openings and coupling beams over height of entire structure

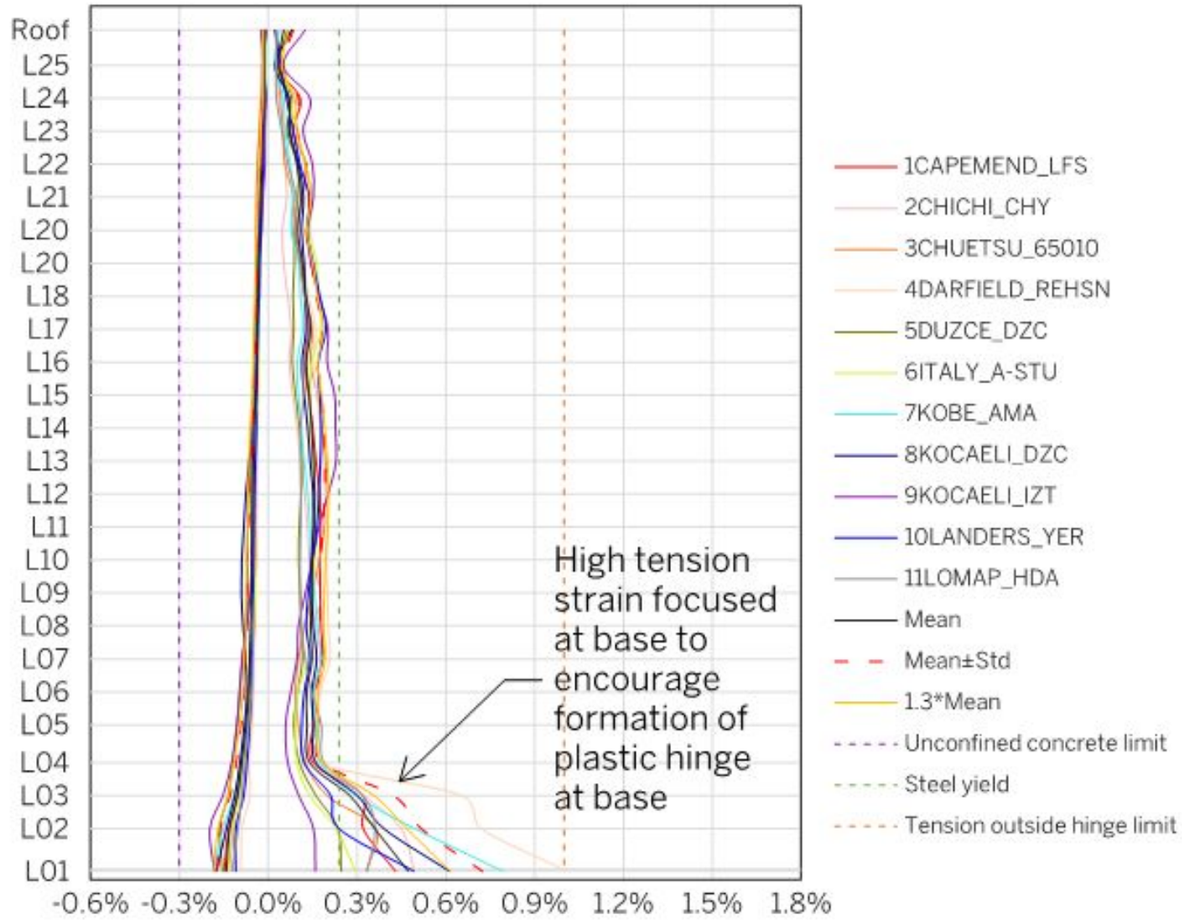
Nonlinear Analysis and Design

Core Wall Design Using NLRHA Procedures



Coupling Beam Rotation

- Moderate coupling beam energy dissipation
- Distributed over full height



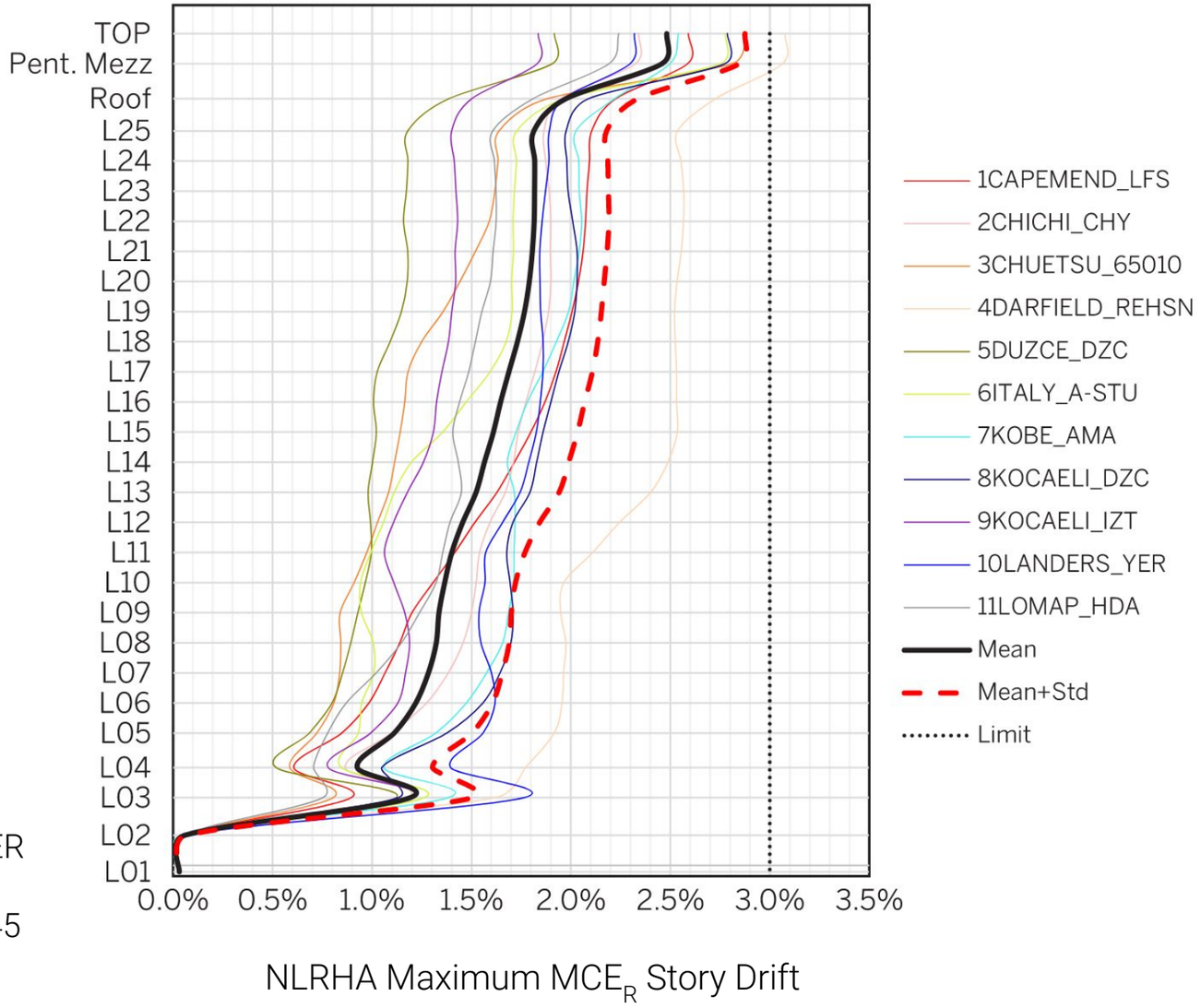
Wall Fiber Strain (%)

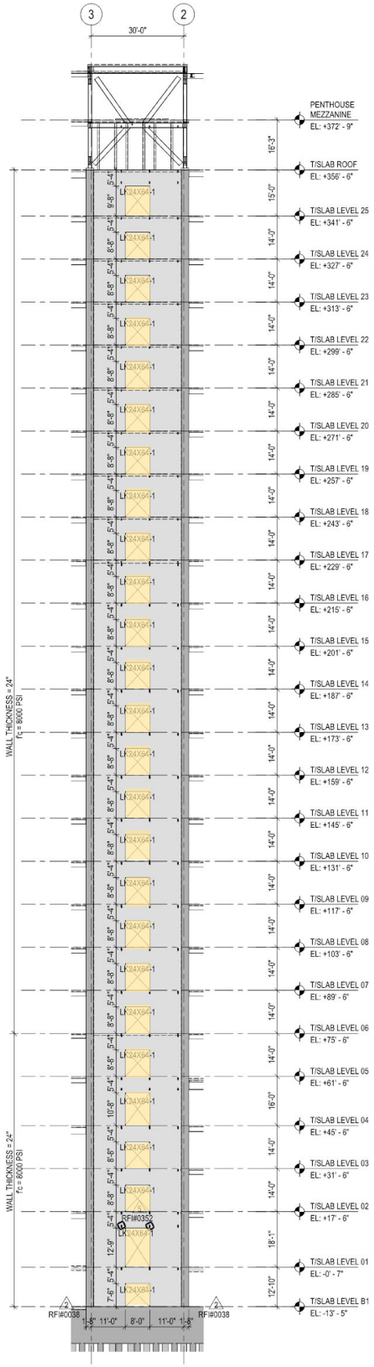
- Low wall steel tension strains above Level 4
- Targeted flexural steel yielding at Levels 1 to 3
- Low concrete compressive strains

Design informed by nonlinear analysis

Nonlinear Analysis and Design

MCE_R Peak Transient Story Drift Ratio





Peak story drift limits per PEER TBI 6.7.1 & 6.7.2

Mean drift ≤ 0.03; Max ≤ 0.045

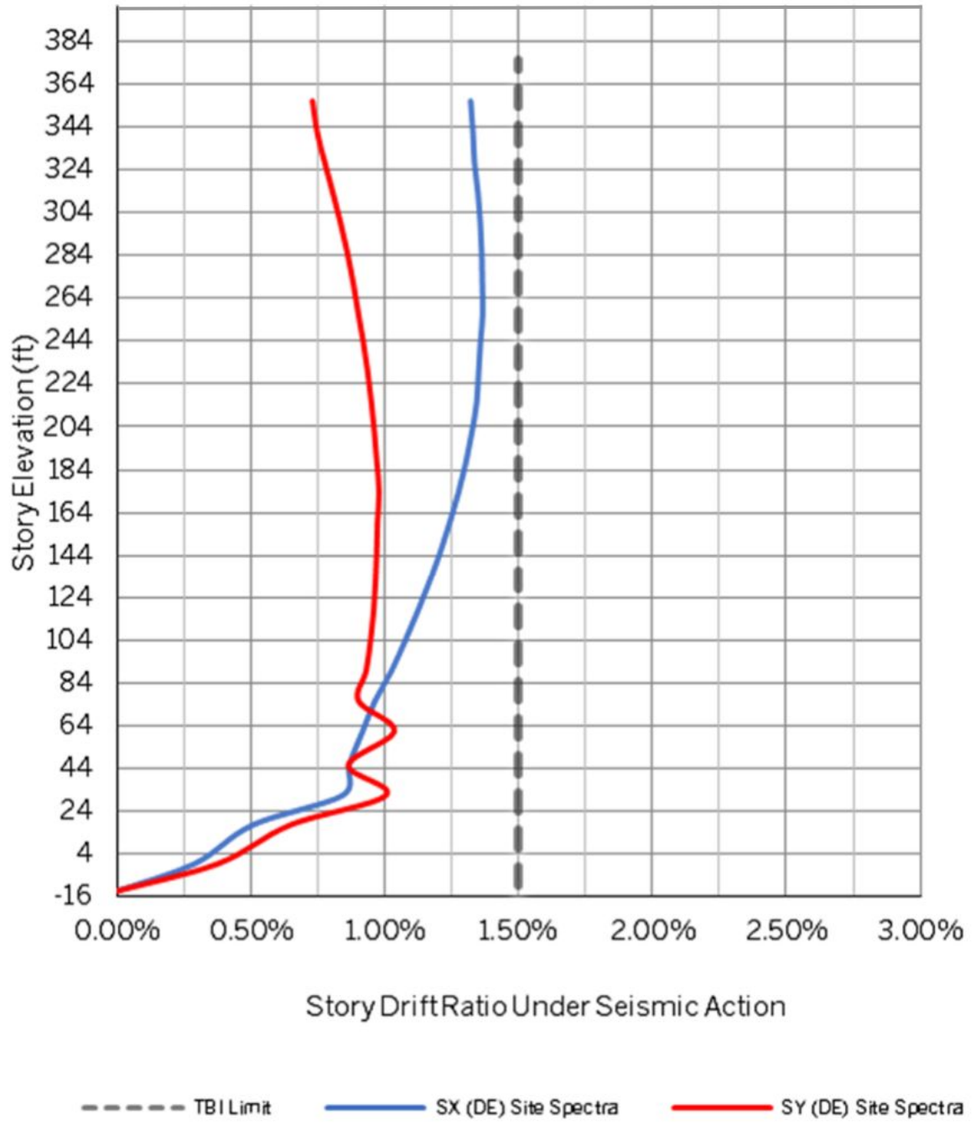
Nonlinear Analysis and Design

Prescriptive Design Code Checks

DE Level Earthquake

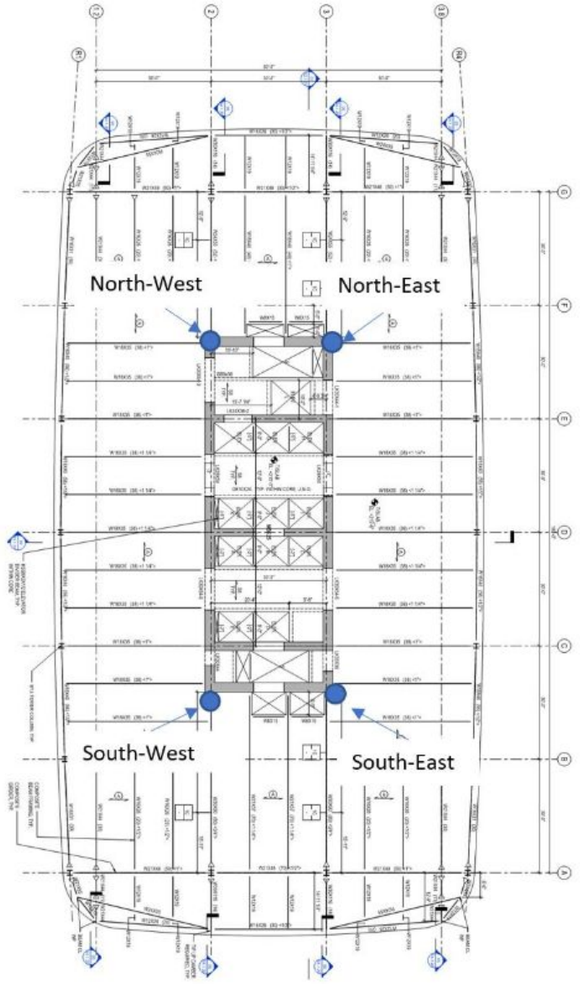
Risk Category III

Story Drift Ratio Limit: 1.5%

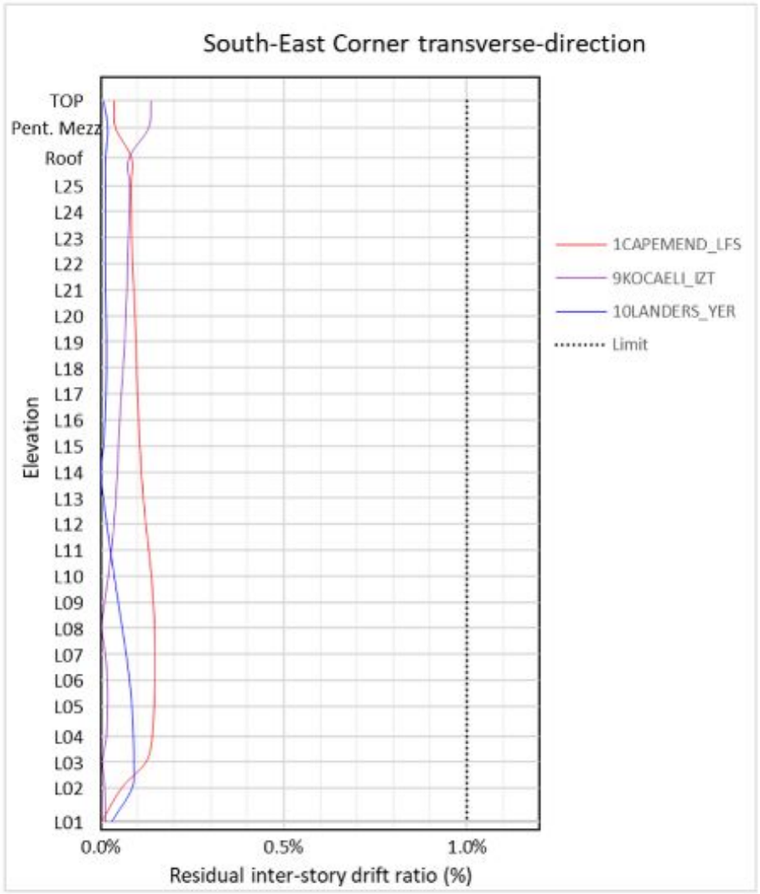


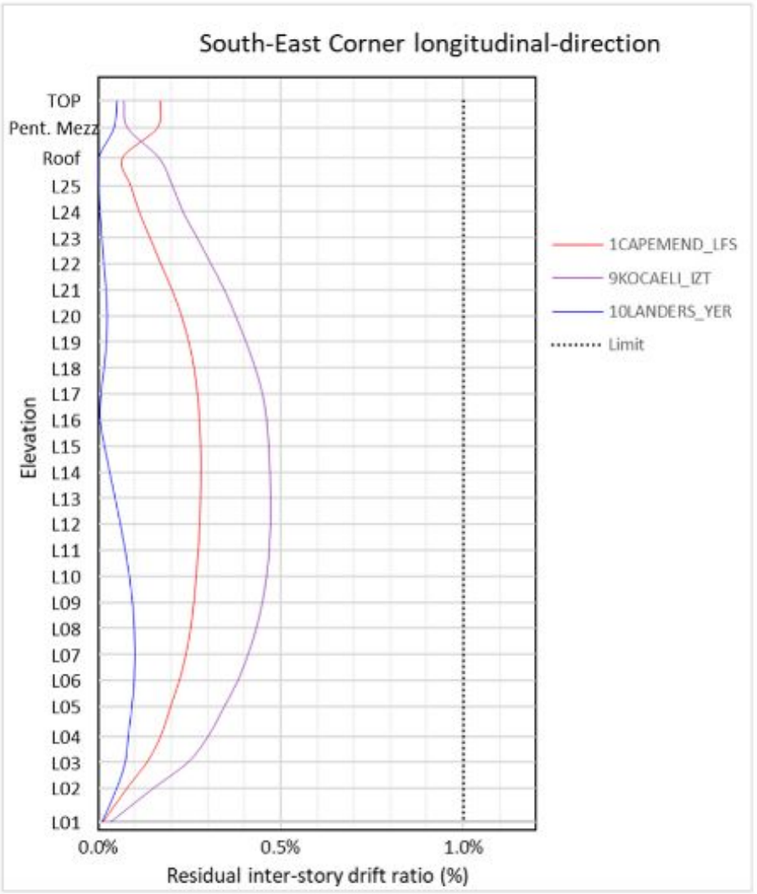
Nonlinear Analysis and Design

MCE_R Absolute Residual Story Drift Ratio



Locations of recorded residual drift





Residual drift limits per PEER TBI 6.7.1 & 6.7.3
Mean residual drift ≤ 0.01; Max ≤ 0.015

Nonlinear Analysis and Design
Exterior Wall Performance Mockup

6.9.3 Cladding Systems

Detail cladding systems, including the cladding itself and cladding connections to the structure, to avoid failure that would result in shedding of the cladding from the building when subjected to the mean of the absolute values of the peak transient story drifts in each story.

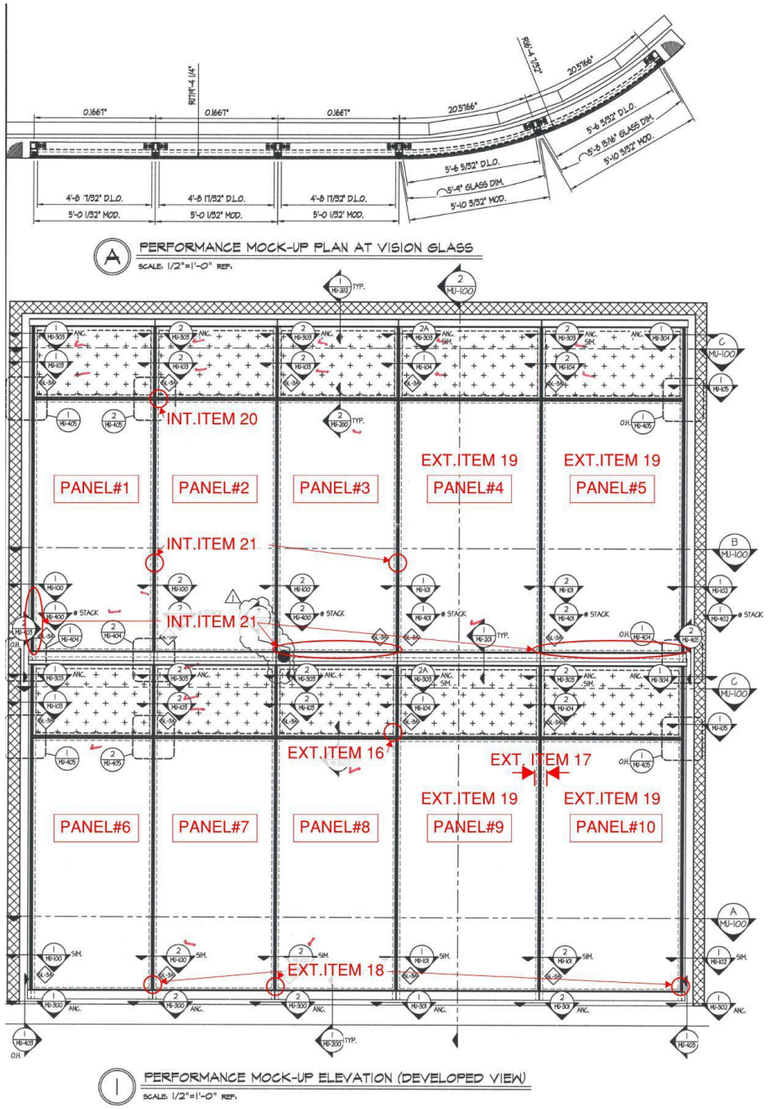
SOM Specification – 08 41 00

Exterior Wall Drift Performance Criteria

- EQ1: 0.75% Service Level
- EQ2: 1.50% Design Level (DE) – Inelastic
- EQ3: 2.50% Maximum Considered (MCE_R) - Nonlinear

Exterior Wall Performance Mockup

EQ3: 4.2” of Displacement (2.5% Drift)



95 State at City Creek
Acknowledgements

Developer Client – City Creek Reserve, Inc.

- Matt Baldwin, Sean Tuite and Kory Jardine

Architect – Skidmore, Owings & Merrill

- Michael Duncan, Steven Sobel, Sean Ragasa, Hardik Udani, Alex Welsh, Ian Crouch

Structural Engineer – Skidmore, Owings & Merrill

- Mark Sarkisian, Peter Lee, Rupa Garai, Jiejing Zhou, Alex Zha, Jaskanwal Chhabra

General Contractor – Okland Construction

Geotechnical Engineer – CEL

- Chris Garris

Seismic Hazards – Lettis Consultants International

- Patricia Thomas, Ivan Wong, Nora Lewandowski

Independent Peer Review Panel

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- Maffei SE – Joe Maffei, Noelle Yuen, Karl Telleen, Saeed Fathali
- Norm Abrahamson – Seismic hazards


ZIONS BANK