Performance Based Seismic Design of Tall RC Core Wall Buildings: State of Practice on the West Coast of the U.S.

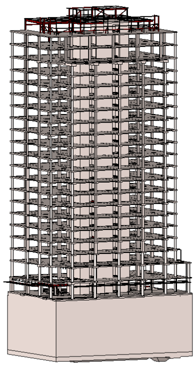
The 2nd JCI & ACI Joint Seminar
-Resilience of Concrete Structures-

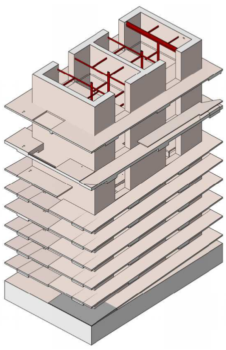
Jeff Dragovich, PhD, SE, FACI

Presentation Outline

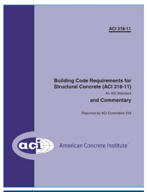
- The "Tall RC Core Wall Building" and Design Guidelines
- Motivation for Performance Based Seismic Design (PBSD) and the Implementation
- Growth of PBSD
- The Process
- Design and Evaluation

The Tall RC Core Wall Building





Resource Documents (Prescriptive Design)

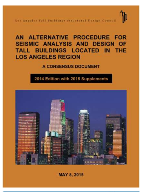


ACI 318: Component Design

IBC: Governing code

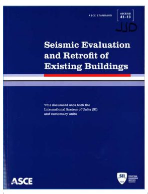
ASCE 7: Loading

Resource Documents (PBSD Methodology)



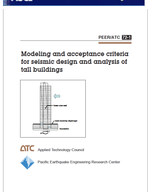
LATBSDC: An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region (2015)

ASCE 41: Seismic Evaluation and Retrofit of Existing Buildings (2013)



PEER TBI: Guidelines for Performance-Based Seismic Design of Tall Buildings (2010)

ATC 72: Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings (2010)



Motivation

- The "Tall RC Core Wall Building" = Special Reinforced Concrete Shear Walls in ASCE 7
  - Height limit = 240 ft (160 ft SDC F) in "high seismic" regions when:
    - No extreme torsional irregularity exists
    - Shear in any wall < 60% total shear for that level
  - Otherwise height limit is 160 ft (100 ft SDC F)
- The alternative is a Dual System with Special Moment Resisting Frames + Special Reinforced Concrete Shear Walls
  - No Height Limit
  - Dual system has significant negative architectural and cost implications when large moment frame beams and columns are placed around the perimeter of the building
- PBSD provides a better indication of structural performance

PBSD and ASCE 7

The design will utilize a performance-based procedure as allowed in Section 1604.4 of the IBC and Section 12.2.1 of ASCE 7.

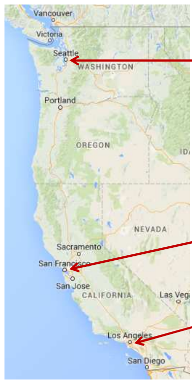
1604.4 Analysis: "Any system or method of construction to be used shall be based on a rational analysis in accordance with well-established principles of mechanics. Such analysis shall result in a system that provides a complete load path capable of transferring loads from their point of origin to the load-resisting elements."

12.2.1 Structural System Selection and Limitations: "…Seismic force-resisting systems that are not contained in Table 12.2-1 are permitted if analytical and test data are submitted that establish the dynamic characteristics and demonstrate the lateral force resistance and energy dissipation capacity to be equivalent to the structural systems listed in Table 12.2-1 for equivalent response modification coefficient, R, system overstrength coefficient, Ω_0, and deflection amplification factor, C_d, values."

The design is also intended to meet the performance-based equivalence criteria of Section 104.11 of the IBC:

104.11 Alternative Materials, Design and Methods of Construction and Equipment: "The provisions of this Code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this Code, provided that any such alternative has been approved. Any alternative material, design, or method of construction shall be approved where the building official finds the proposed design is satisfactory and complies with the intent of the provisions of this Code, and that the material, method, or work offered is, for the purpose intended, at least the equivalent of that prescribed in this Code in quality, strength, effectiveness, fire resistance, durability, and safety."

PBSD Project Summary



Estimates from 3 West Coast Building Departments

Seattle (44 Total):

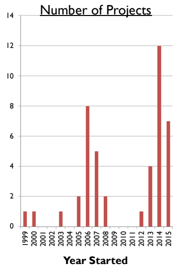
Number	Status
16	Peer Review Underway
1	Peer Review Complete
10	Under Construction
11	Constructed
3	Not Built
3	Peer Review Not Complete

San Francisco (17 Total):
- 17 Permitted
- 11 in Progress

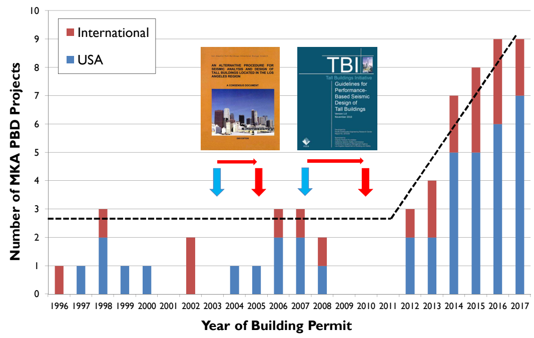
Los Angeles (27 Total):
- 5 Completed
- 22 In Progress

Summary of PBSD – City of Seattle

ID	Description	Lateral System	Year Started	Status
1	43 Story Ofc/Residential	Concrete Core	2015	Peer Review Underway
2	40 Story Hotel/Residential	Concrete Core - Dual System	2015	Peer Review Underway
3	40 Story 525,000 Sq Ft Residential Bldg	Concrete Core	2015	Peer Review Underway
4	59 Story Ofc/Residential	Concrete Core	2015	Peer Review Underway
5	34 Story Ofc Bldg	Concrete Core	2015	Peer Review Underway
6	15 Story Medical Clinic/Office	Concrete Core	2015	Peer Review Underway
7	17 Story Hospital	Concrete Core	2015	Peer Review Underway
8	40 Story Residential Bldg	Concrete Core	2014	Peer Review Underway
9	41 Story Residential Bldg	Concrete Core	2014	Peer Review Underway
10	40 Story 589,000 Sq Ft Residential Bldg	Concrete Core	2014	Peer Review Underway
11	37 Story Condo and 11 Story Ofc on Comm BaseLI	Concrete Core	2014	Peer Review Underway
12	Hedreen Hotel 41 Story 1260 Rm Hotel	Concrete Core	2014	Peer Review Underway
13	38 Story 1,600,000 Office Bldg	Concrete Core	2014	Peer Review Underway
14	32 Story 400,000 Sq Ft Residential and Office Bldg	Concrete Core	2014	Peer Review Underway
15	24 Story 420,000 Sf Ft Ofc Bldg	Concrete Core	2014	Peer Review Underway
16	38 Story Hotel/Residential Bldg	Concrete Core	2014	Peer Review Underway
17	39 Story 513,000 Sq Ft Residential Bldg	Concrete Core - Dual System	2014	Peer Review Complete
18	21 Story Ofc Bldg	Concrete Core	2014	Under Construction
19	24 Story Residential	Concrete Core	2014	Under Construction
20	40 Story Residential Bldg	Concrete Core	2013	Under Construction
21	39 Story 500,000 Sq Ft Residential Bldg	Concrete Core	2013	Under Construction
22	1,600,000 37 story Ofc Bldg	Concrete Core	2013	Under Construction
23	38 story 1,700,000 Sq Ft Ofc Bldg	Concrete Core	2013	Under Construction
24	24 Story Residential	Concrete Core W/Fiber Reinforced CB	2012	Constructed
25	39 Story Residential	Concrete Core	2008	Constructed
26	39 Story Hotel/Residential	Concrete Core	2008	Under Construction
27	39 Story Office Bldg	Concrete Core	2007	Under Construction
28	44 Story Office	Concrete Core W/Exterior Steel Bracing	2007	Under Construction
29	40 Story Residential Twin Towers	Concrete Core	2007	Under Construction
30	29 story Residential	Concrete Core	2007	Not Built
31	10 Story Storage	Concrete Core w/Partial X Coupling Beams	2007	Constructed
32	39 Story Hotel/Residential	Concrete Core	2006	Not Built
33	27 story Residential	Concrete Core	2006	Constructed
34	39 story Residential	Concrete Core	2006	Constructed
35	34 Story Residential	Concrete Core	2006	Constructed
36	30 Story Residential	Concrete Core	2006	Peer Review Not Complete
37	34 Story Office	Concrete Core	2006	Constructed
38	27 Story Office	Concrete Core	2006	Peer Review Not Complete
39	35 Story Residential	Concrete Core	2006	Peer Review Not Complete
40	31 story Ofc/Residential	Concrete Core	2005	Not Built
41	38 Story Hotel	Concrete Core	2005	Constructed
42	42 story Ofc Bldg	Concrete Core	2003	Constructed
43	34 Story Residential	Concrete Core	2000	Constructed
44	40 Story Office	Concrete Core	1999	Constructed



Projected Growth of PBSD[1]

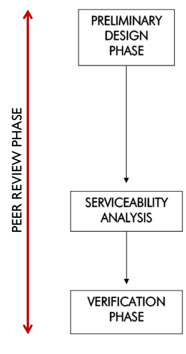


1. Source: Magnusson Klemencic Associates

PBSD Guidelines

- The Objective is to provide buildings the capability to:
  - Withstand Maximum Considered Earthquake (MCE) with low probability (<10%) of collapse
  - Withstand the Design Earthquake (DE = 2/3 MCE) without significant hazards
  - Withstand frequent earthquakes (43 year return period) with limited damage (Serviceability Earthquake)
- Identification of inelastic and elastic actions
  - Deformation Controlled: Reliable inelastic deformation
    - Core wall flexure, Coupling beams
  - Force Controlled: Inelastic deformation capacity not assured, designed to be essentially elastic
    - Core wall shear, diaphragm shear, basement wall shear, outrigger column axial load, mat foundation shear
    - $U_{design} = 1.5\ U_{MCE}$

Design and Verification Process



Elastic Analysis And Design
Use response spectrum analysis at DE level:
- Design structural components that are anticipated to yield based on code level demands (R=6)
- Specified material properties
- Perform initial design on components that are to remain essentially elastic:

$$U_{design} = 2.5{*}U_{DE}$$

Serviceability Analysis
- Expected material properties
- Verify that Engineering Demand Parameters (EDP's) such as story drift, coupling beam rotation, shear wall shear demand are meet serviceability acceptance criteria for a 43-year earthquake return period

Nonlinear Time History Analysis Evaluation
Design verification using MCE nonlinear response history analysis:
- 7 ground motion pairs min, for stiff and flexible transfer diaphragms
- Check EDP against acceptance criteria

Load Combinations

- Service Level

$$1.0D + 0.25L \pm 1.0E_{service}$$

- Design Earthquake

$$(1.2 + 0.2S_{DS})D + Q_E + (f_1L+f_2S)$$

$$(0.9 - 0.2S_{DS})D + Q_E + 1.6H$$

- MCE Level

$$1.0D + 0.25L + 1.0E$$

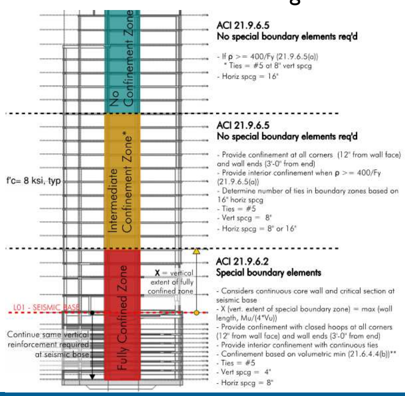
MCE Acceptance Criteria

Item	Value (Reference)
Story Drift	3.0 percent under MCE, taken as the average of 7 analyses; 4.5 percent maximum from any single analysis (PEER TBI Guidelines)
Residual Story Drift	1 percent taken as the average of 7 analyses; 1.5 percent from any single analysis. (PEER TBI Guidelines)
Coupling Beam Rotation	0.06 radian rotation limit for diagonally-reinforced beams, 0.04 radian rotation limit for conventionally-reinforced beams. Rotations taken as the average of 7 analyses. (Acceptance Criteria Reference 1)
Core Wall Reinforcement Axial Strain	Rebar Tensile Strain = 0.05 in tension and 0.02 in compression, taken as the average of 7 analyses. (Acceptance Criteria Reference 2)
Core Wall Confined Concrete Axial Strain	Fully confined compression strain of 0.015, taken as the average of 7 analyses. (Acceptance Criteria Reference 3)
Core Wall Unconfined Concrete Axial Strain	Fully confined compression strain of 0.003, taken as the average of 7 analyses. (ACI 318-11)
Gravity Columns	DCR limited to 1.0. DCR calculated using expected material properties and code-specified phi-factors. Demand taken as 1.5 times the average demand from the 7 analyses. (PEER TBI Guidelines)

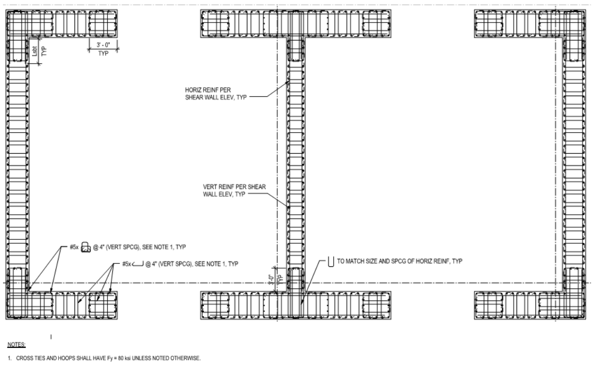
MCE Acceptance Criteria

Item	Value (Reference)
Core Wall Shear	DCR limited to 1.0. DCR calculated using expected material properties. ϕ=1.0 provided ε_c <= 0.005 and ε_s <= 0.01. If strains are larger than these limits, code-specified phi-factors will be used. Demand taken as 1.5 times the average demand from the 7 analyses. (TBDC Meeting Minutes)
Transfer Diaphragm (Level 1)	DCR limited to 1.0. DCR calculated using expected material properties and code-specified phi-factors. Demand taken as 1.5 times the average demand from the 7 analyses. (PEER TBI Guidelines)
Collectors	DCR limited to 1.0. DCR calculated using expected material properties and code-specified phi-factors. Demand taken as 1.5 times the average demand from the 7 analyses. (PEER TBI Guidelines)
Basement Walls	DCR limited to 1.0. DCR calculated using expected material properties and code-specified phi-factors. Demand taken as 1.5 times the average demand from the 7 analyses. (PEER TBI Guidelines)
Foundation Flexure	DCR limited to 1.0. DCR calculated using expected material properties and code-specified phi-factors. Demand taken as 1.0 times the average demand from the 7 analyses. (PEER TBI Guidelines)
Foundation Shear	DCR limited to 1.0. DCR calculated using expected material properties and code-specified phi-factors. Demand taken as 1.5 times the average demand from the 7 analyses. (PEER TBI Guidelines)

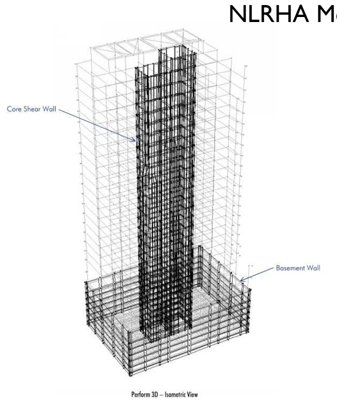
Core Wall Flexural Design

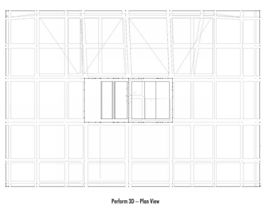


Core Wall Detailing



NLRHA Modeling

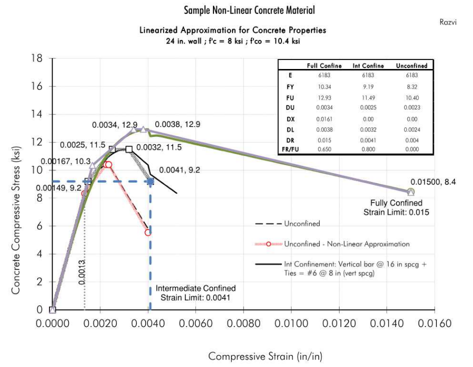




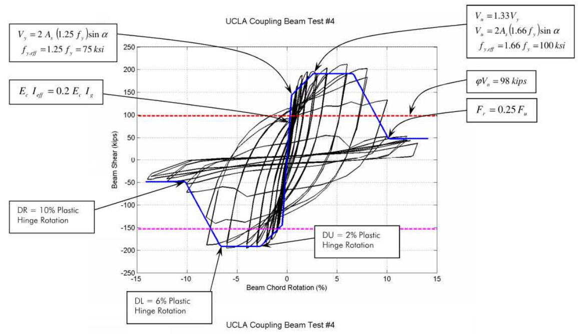
Model Features:

- Fiber model for core axial/flexure
- Inelastic shear hinges for coupling beams
- Inelastic flexural hinges for outrigger slabs
- Elastic:
  - Core wall shear
  - Outrigger columns
  - Transfer diaphragms

Concrete Material Modeling

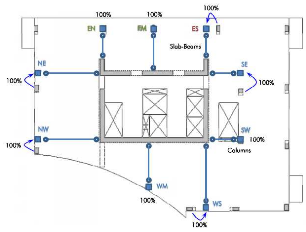


Coupling Beam Modeling

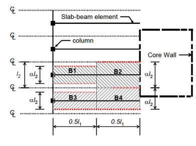


Ref: (Naish et al) *Reinforced Concrete Link Beams: Alternative Details for Improved Construction*, UCLA-SGEL Report 2009/06

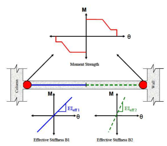
Outrigger Slab Modeling



Representative Outrigger Idealization



Elastic Slab Beam Model

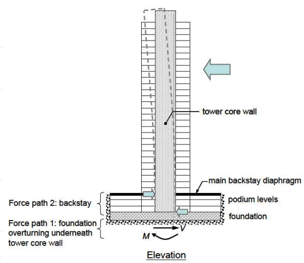


Hinge Model

The objective of the slab outrigger modeling is to capture the increase in axial loads in the gravity columns, which is verified at U = 1.0D + 0.25L + 1.0E_{MCE}

Hinge model is calibrated against reference: (Klemencic et al) *Performance of Post-Tensioned Slab-Column Connections*, PTI Journal, December 2006

The Transfer Podium

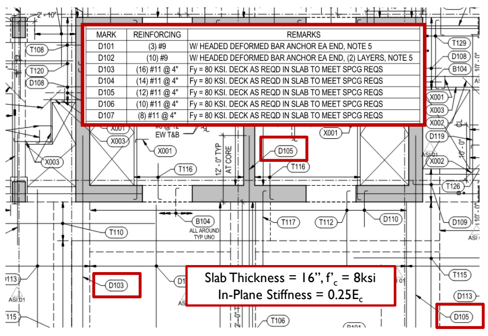


Modeling Issues:

- Two levels of podium diaphragm stiffnesses are investigated:
  - Upper bound = 0.25E_c to 0.5E_c
  - Lower bound = 0.10E_c
- Results in 14 minimum NLRHA runs
- An upper bound stiffness approaching 0.5E_c may result in a podium diaphragm with significant demands (24"+ slab)!
- The assumed upper bound stiffness is a widely debated topic
- Transfer diaphragm design is based on U=1.5*U_{MCE}

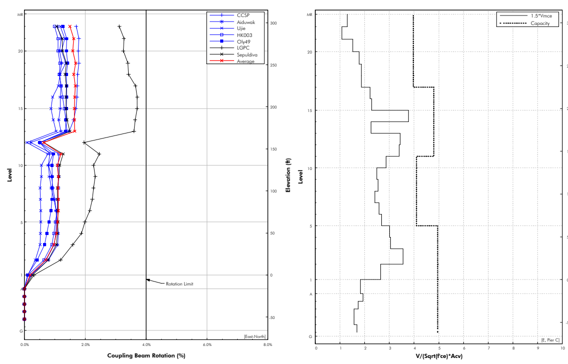
Ref: ATC 72-1

The Transfer Podium – Collector Reinforcement

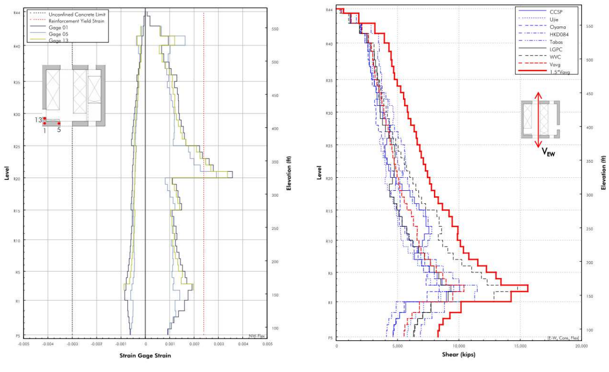


Reinforcement Plan – Podium Level

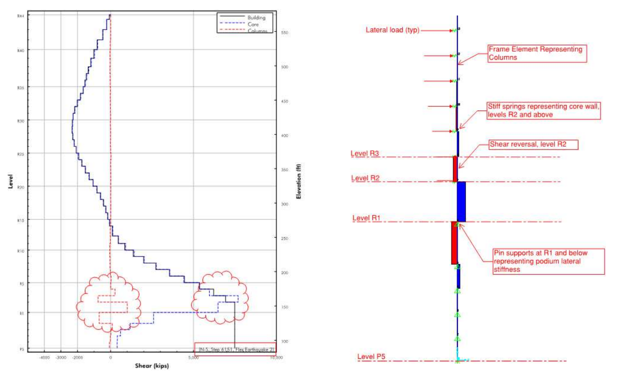
NLRHA Verification



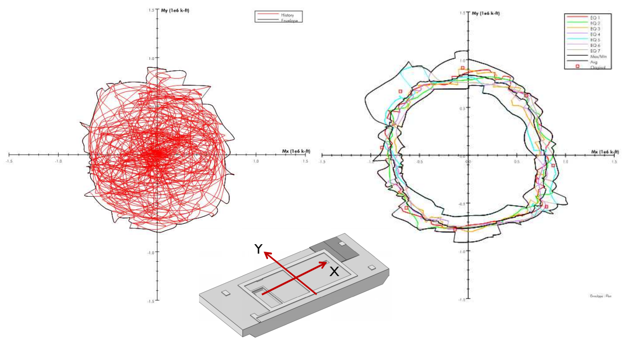
NLRHA Verification



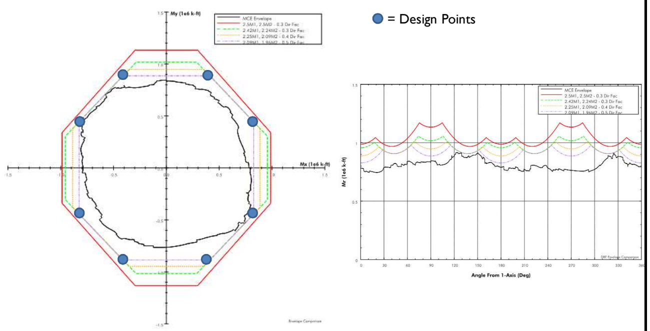
Subtle Issue – Gravity Column Effect



Foundation Demands



Foundation Demands

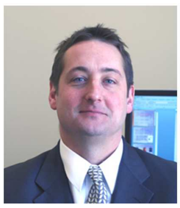


PostScript

- The trend in the use of PBSD on the west coast of the U.S. (and internationally) is increasing
- The Future (needs):
  - Improved modeling capabilities
  - Refinement of modeling criteria and acceptance criteria
- Acknowledgements
  - John Hooper, Director of Earthquake Engineering, Magnusson Klemencic Associates
  - Steve Pfeiffer, City of Seattle
  - Gary Ho, City of San Francisco
- Contact Information
  - Jeff Dragovich: jeff.dragovich@gmail.com

My Involvement with ACI

- Began in 2000 when I presented at an ACI committee 374 meeting. I have been active with ACI technical committees ever since.
- Current Chair of committee 374



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ACI 369 Seismic Repair and Rehabilitation

Associate
ACI 133 Disaster Reconnaissance
ACI 447 Finite Element Analysis

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