Performance Based Seismic Design Guidelines for Tall Buildings and their Applications

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What is a Tall Building?

- Overall height as a measure
  - ✓ Some codes such as ASCE 7 impose limits on lateral systems to be used based on height
- Aspect ratio as a measure
- Vibration period as a measure
- Prevalence of higher modes in response as a measure
- No universally accepted definition exists but you know one when you see one!

Should tall buildings be treated like other buildings?

- Tall buildings are occupied by hundreds if not thousands of people
- The consequence of failure of tall buildings is much more severe than an ordinary building
- Codes provide a “one size fits all” approach to seismic design.
- Tall buildings as small class of specialized structures will perform better during earthquakes if special attention is afforded to their individual characteristics.
- Prescriptive codes are not equipped with means to distinguish these differences.

Why prescriptive codes are not suitable?

- Because they simply cannot give you what you need.
- Linear analysis is incapable of accurately predicting collapse and failure which are inherently nonlinear
- The overwhelming majority of construction in United States and worldwide consists of low-rise buildings

- Prescriptive provisions are not generally written with tall buildings in mind.

We will examine two guidelines.

TBI

Tall Buildings Initiative

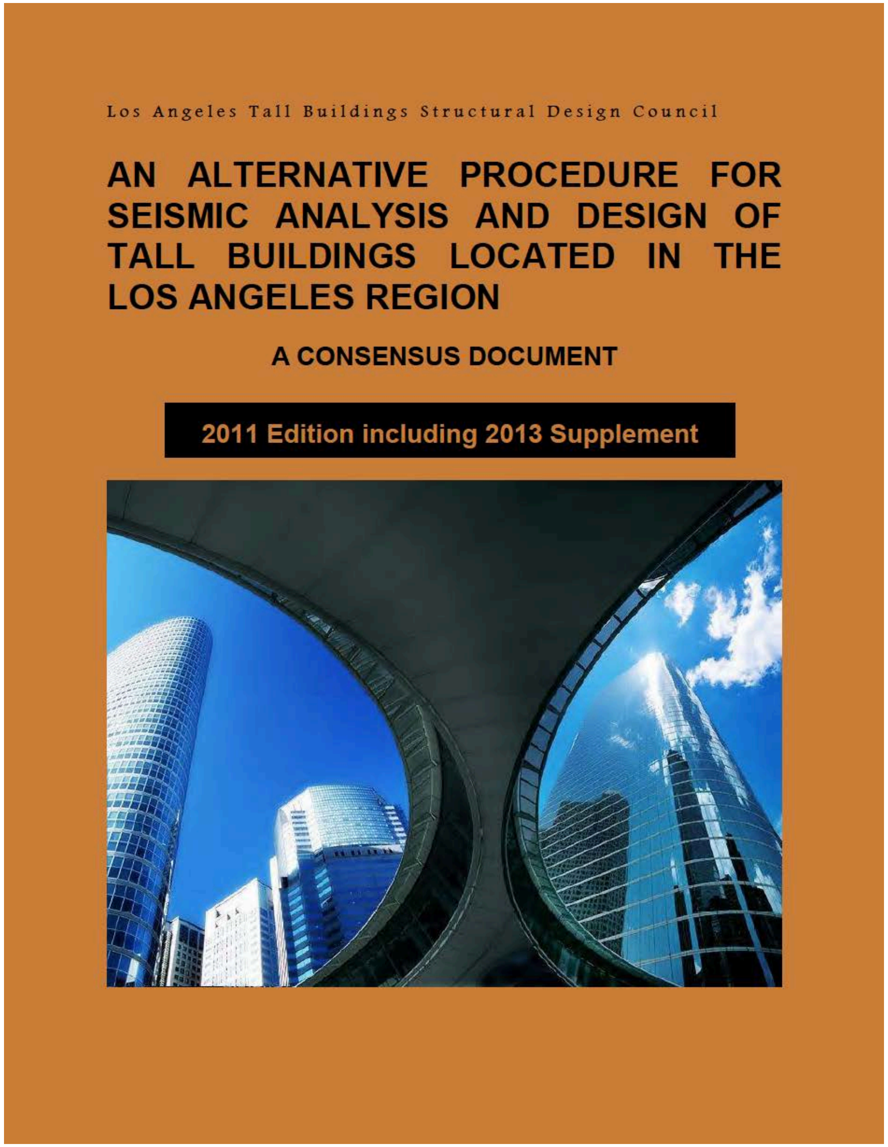
Guidelines for Performance-Based Seismic Design of Tall Buildings

Version 1.0
November 2010

Developed by
Pacific Earthquake Engineering Research Center
Report No. 2010/05

Sponsored by
Charles Pankow Foundation
California Seismic Safety Commission
California Emergency Management Agency
Los Angeles Department of Building and Safety

PEER



Los Angeles Tall Buildings Structural Design Council

AN ALTERNATIVE PROCEDURE FOR SEISMIC ANALYSIS AND DESIGN OF TALL BUILDINGS LOCATED IN THE LOS ANGELES REGION

A CONSENSUS DOCUMENT

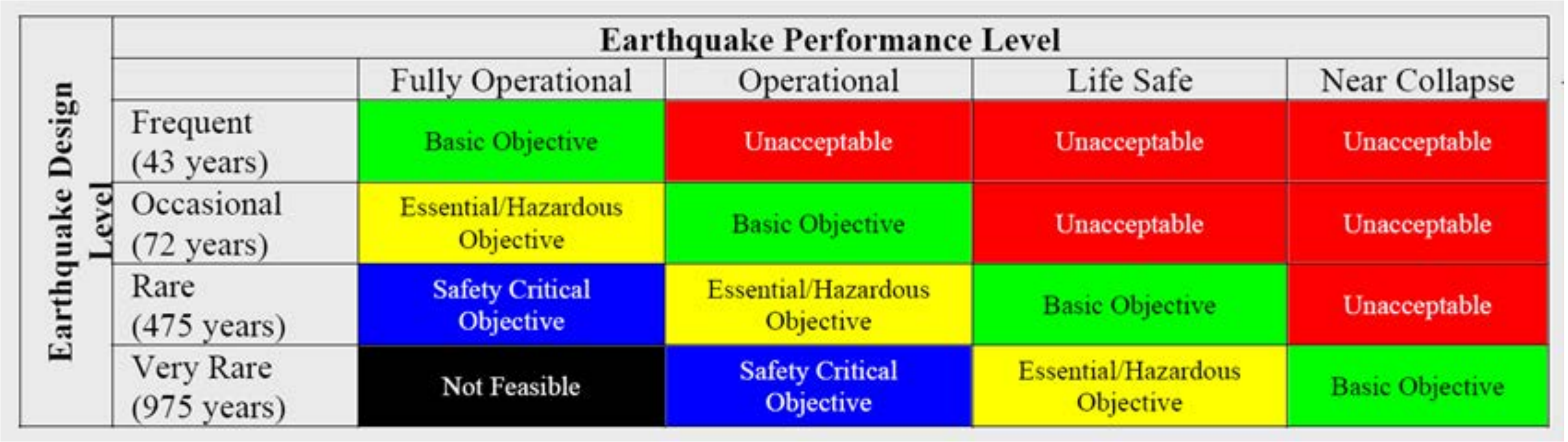
2011 Edition including 2013 Supplement

ASCE 41and Tall Building Design Guidelines

- ASCE41 is officially intended for seismic rehabilitation of existing structures
- However, its component-based performance limits for NDP are routinely referenced by guidelines for performance based design of tall buildings
- Engineers who believe ASCE 41limits are too conservative, or are not applicable to their project, conduct tests to establish appropriate limits
- Peer review approval is always necessary for any deviation from ASCE 41

Common Performance Objectives

- **SEAOC-99**



Earthquake Design Level	Earthquake Performance Level			
	Fully Operational	Operational	Life Safe	Near Collapse
Frequent (43 years)	Basic Objective	Unacceptable	Unacceptable	Unacceptable
Occasional (72 years)	Essential/Hazardous Objective	Basic Objective	Unacceptable	Unacceptable
Rare (475 years)	Safety Critical Objective	Essential/Hazardous Objective	Basic Objective	Unacceptable
Very Rare (975 years)	Not Feasible	Safety Critical Objective	Essential/Hazardous Objective	Basic Objective

- **ASCE 41**
  - **Similar objectives permitted. Emphasis on two events:**
    - 475 years (10% in 50 years), and
    - 2,475 years (2% in 50 years)

- **Tall Building Design Guidelines**
  - **Serviceability: 43 years**
  - **Collapse Prevention: 2,475 years**

Analytical Procedures

- ASCE-41 permits four types of analyses:
    1. Linear elastic static procedure (LSP)
    2. Linear dynamic procedure (LDP) or response spectrum analysis
    3. Non-linear static procedure (NSP) commonly referred to as the push-over analysis, and
    4. Dynamic nonlinear response analysis (NDP).

- Tall Building Design Guidelines permit only two:
    1. 3D LDP or NDP for serviceability check
    2. 3D NDP for all other checks

PEER-TBI & LATBSDC Performance Objectives

1. **Serviceable behavior under events having a 50% probability of being exceeded in 30 years (43 year return period)**
    - **building structural and nonstructural components retain their general functionality during and after earthquake**
    - **Repairs, if necessary, are expected to be minor and could be performed without substantially affecting the normal use and functionality of the building**
2. **A low probability of collapse under events having a 2% probability of being exceeded in 50 years (2,475 year return period)**
    - **Demands are checked for all structural members (lateral as well as gravity system)**
    - **Claddings and their connections to the structure must accommodate MCE displacements without failure**

PEER-TBI & LATBSDC Provisions

1. Use 2.5% damping instead of 5% damping but permit DCR = 1.5 for deformation controlled members for serviceability.
2. 2011 LATBSDC limits DCR to 0.70 for force controlled members in serviceability check.
3. 2010 PEER requirements for collapse prevention are more elaborate and detailed than 2011 LATBSDC
4. No minimum base shear capacity requirement

Design Procedures

- None of the guidelines tell you how to design
- For example, 2011 LATBSDC states:
  - ✓ Use Capacity Design Techniques
  - ✓ Develop Project-specific Design Criteria, and
  - ✓ Clearly define where nonlinearity can occur and make sure it does not occur elsewhere
  - ✓ Recommends preferred zones of nonlinearity
- But they do not explain how the engineer is supposed to achieve this design.

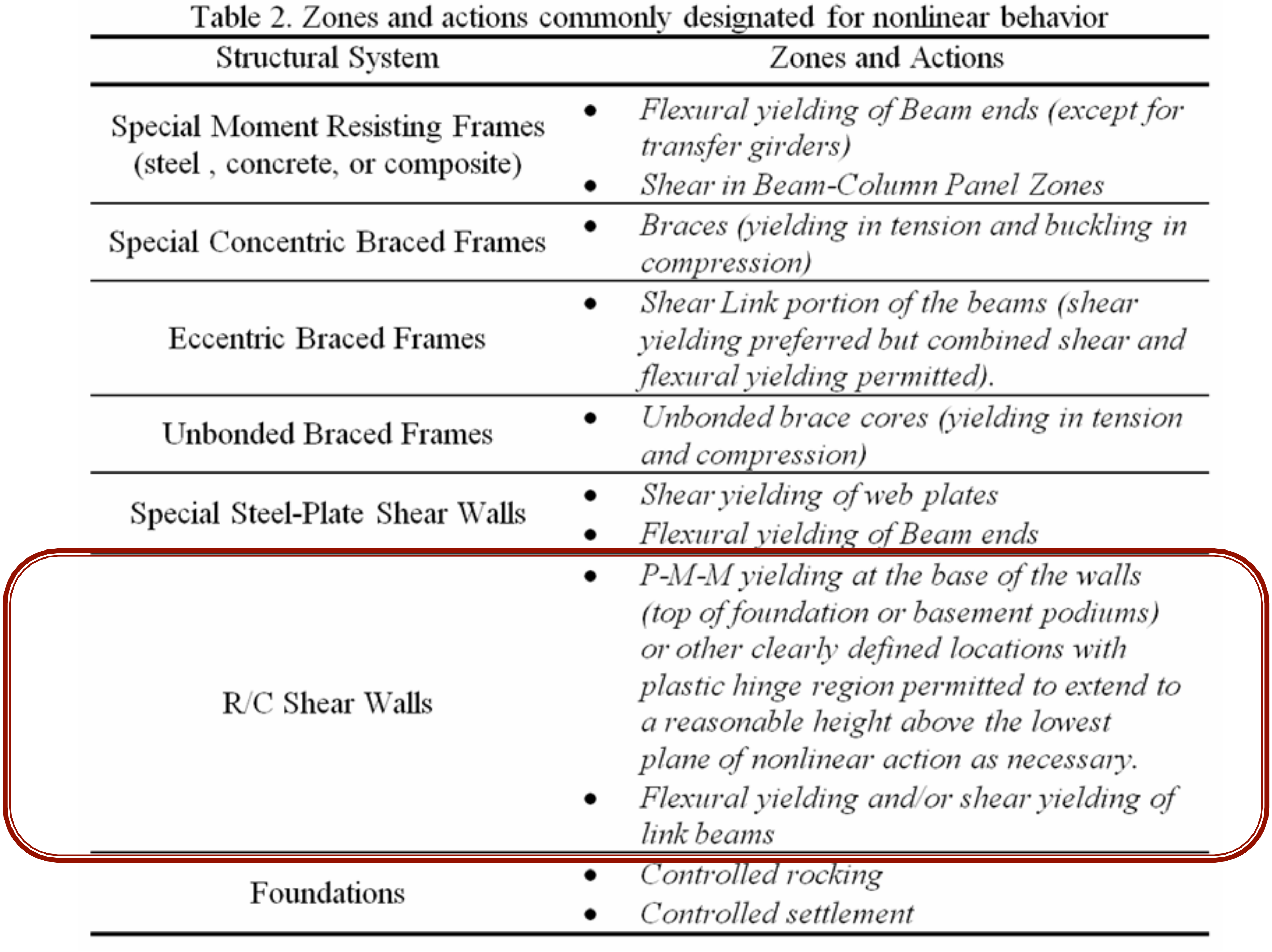


Table 2. Zones and actions commonly designated for nonlinear behavior

Structural System	Zones and Actions
Special Moment Resisting Frames (steel , concrete, or composite)	• *Flexural yielding of Beam ends (except for transfer girders)* • *Shear in Beam-Column Panel Zones*
Special Concentric Braced Frames	• *Braces (yielding in tension and buckling in compression)*
Eccentric Braced Frames	• *Shear Link portion of the beams (shear yielding preferred but combined shear and flexural yielding permitted).*
Unbonded Braced Frames	• *Unbonded brace cores (yielding in tension and compression)*
Special Steel-Plate Shear Walls	• *Shear yielding of web plates* • *Flexural yielding of Beam ends*
R/C Shear Walls	• *P-M-M yielding at the base of the walls (top of foundation or basement podiums) or other clearly defined locations with plastic hinge region permitted to extend to a reasonable height above the lowest plane of nonlinear action as necessary.* • *Flexural yielding and/or shear yielding of link beams*
Foundations	• *Controlled rocking* • *Controlled settlement*

Source: 2011 LATBSDC

Evaluation Procedures

- **All guidelines require a three-dimensional detailed mathematical model of the physical structure**
- **Realistic estimates of stiffness and damping**
- **Expected material properties for ductile elements**
- **Specified material properties for brittle elements**

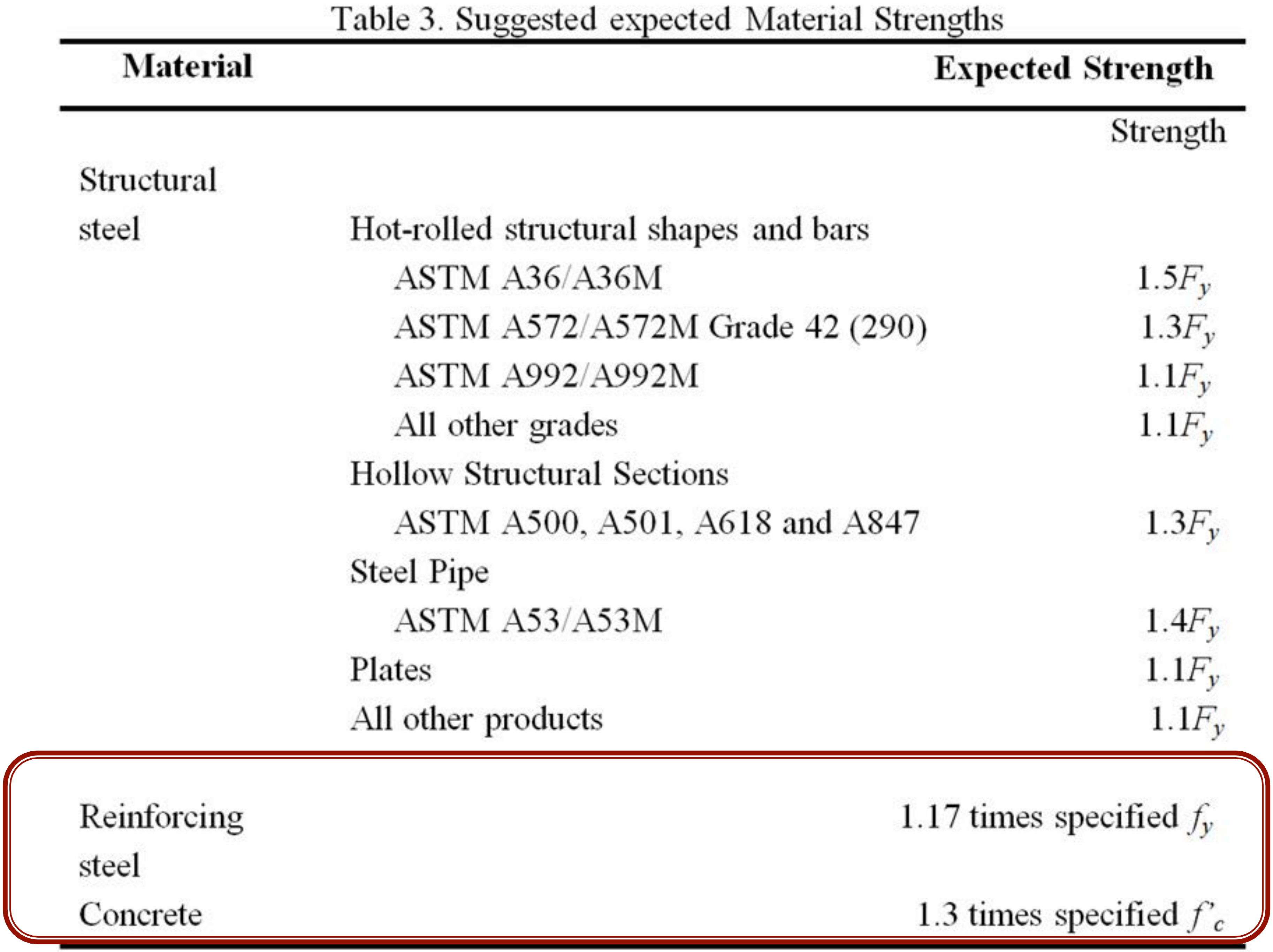


Table 3. Suggested expected Material Strengths

Material		Expected Strength
		Strength
Structural steel	Hot-rolled structural shapes and bars	
	ASTM A36/A36M	$1.5F_y$
	ASTM A572/A572M Grade 42 (290)	$1.3F_y$
	ASTM A992/A992M	$1.1F_y$
	All other grades	$1.1F_y$
	Hollow Structural Sections	
	ASTM A500, A501, A618 and A847	$1.3F_y$
	Steel Pipe	
	ASTM A53/A53M	$1.4F_y$
	Plates	$1.1F_y$
	All other products	$1.1F_y$
Reinforcing steel		1.17 times specified f_y
Concrete		1.3 times specified f'_c

Source: 2011 LATBSDC

Effective Stiffness Values for Linear Analysis

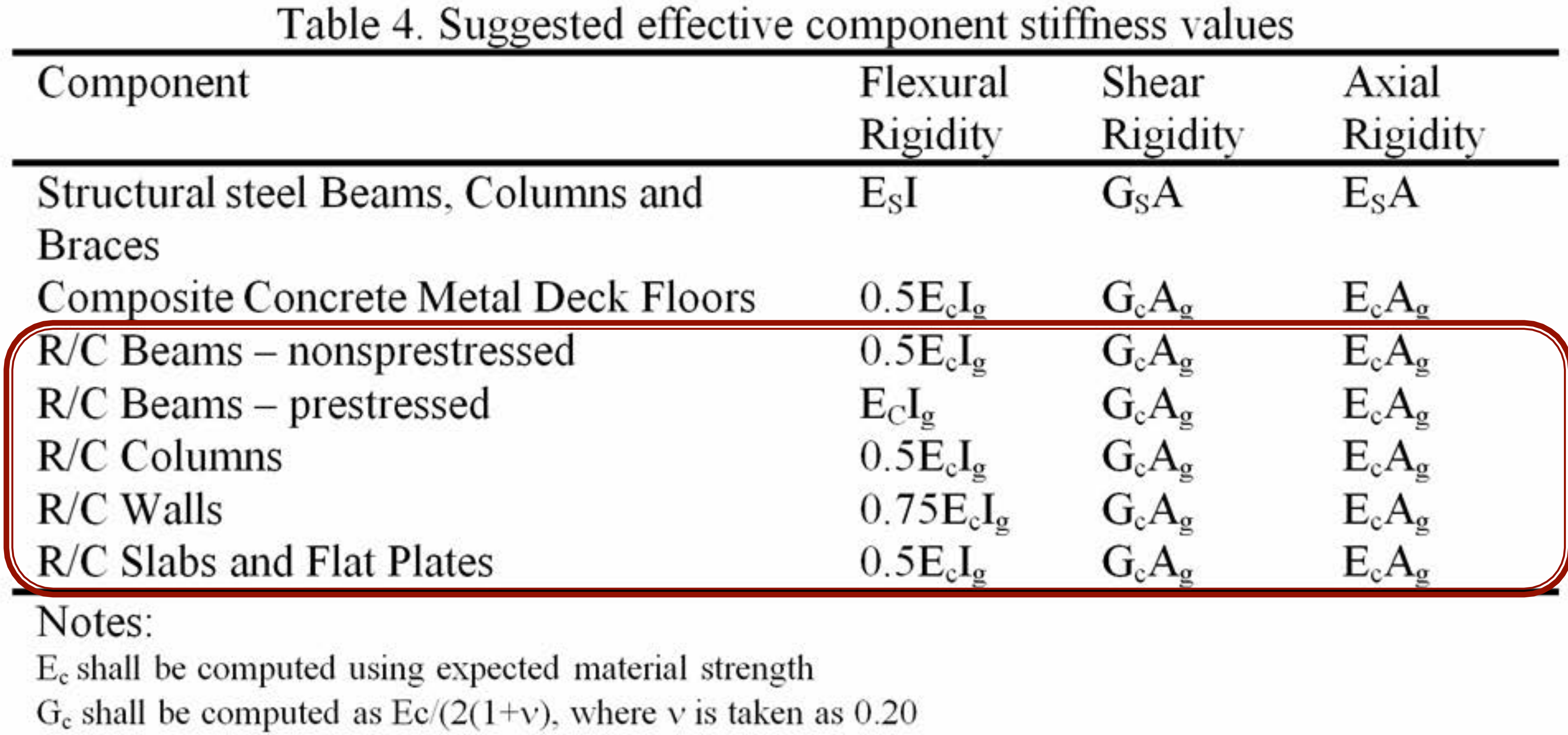


Table 4. Suggested effective component stiffness values

Component	Flexural Rigidity	Shear Rigidity	Axial Rigidity
Structural steel Beams, Columns and Braces	E_SI	G_SA	E_SA
Composite Concrete Metal Deck Floors	$0.5E_cI_g$	G_cA_g	E_cA_g
R/C Beams – nonsprestressed	$0.5E_cI_g$	G_cA_g	E_cA_g
R/C Beams – prestressed	E_CI_g	G_cA_g	E_cA_g
R/C Columns	$0.5E_cI_g$	G_cA_g	E_cA_g
R/C Walls	$0.75E_cI_g$	G_cA_g	E_cA_g
R/C Slabs and Flat Plates	$0.5E_cI_g$	G_cA_g	E_cA_g

Notes:

E_c shall be computed using expected material strength

G_c shall be computed as $Ec/(2(1+\nu)$, where ν is taken as 0.20

Source: 2008 LATBSDC, 2010 PEER

Effective Stiffness Values for Linear Analysis

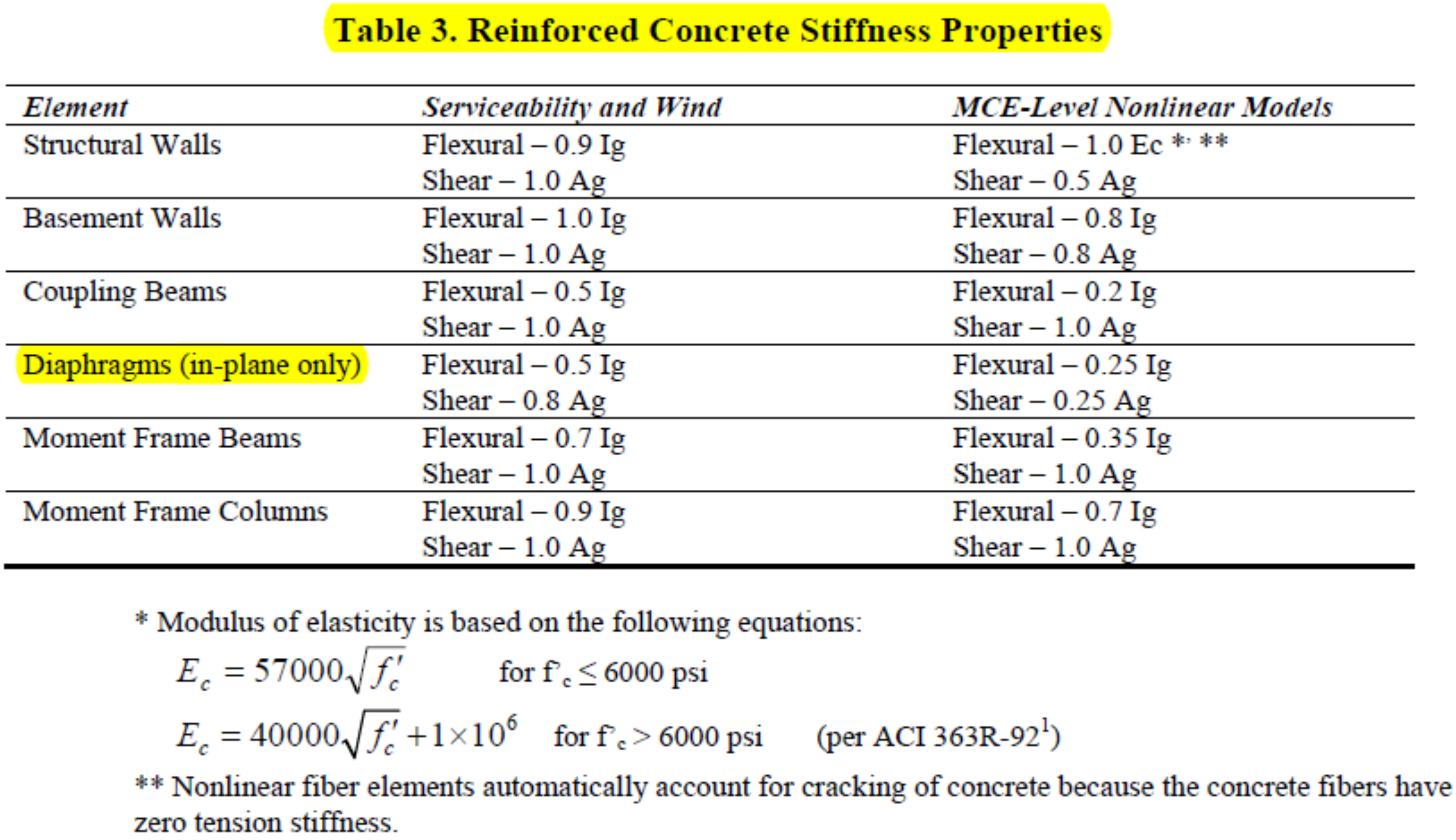


Table 3. Reinforced Concrete Stiffness Properties

Element	*Serviceability and Wind*	*MCE-Level Nonlinear Models*
Structural Walls	Flexural – 0.9 Ig Shear – 1.0 Ag	Flexural – 1.0 Ec *, ** Shear – 0.5 Ag
Basement Walls	Flexural – 1.0 Ig Shear – 1.0 Ag	Flexural – 0.8 Ig Shear – 0.8 Ag
Coupling Beams	Flexural – 0.5 Ig Shear – 1.0 Ag	Flexural – 0.2 Ig Shear – 1.0 Ag
Diaphragms (in-plane only)	Flexural – 0.5 Ig Shear – 0.8 Ag	Flexural – 0.25 Ig Shear – 0.25 Ag
Moment Frame Beams	Flexural – 0.7 Ig Shear – 1.0 Ag	Flexural – 0.35 Ig Shear – 1.0 Ag
Moment Frame Columns	Flexural – 0.9 Ig Shear – 1.0 Ag	Flexural – 0.7 Ig Shear – 1.0 Ag

* Modulus of elasticity is based on the following equations:

$$E_c = 57000\sqrt{f'_c} \qquad \text{for } f'_c \leq 6000 \text{ psi}$$

$$E_c = 40000\sqrt{f'_c} + 1\times10^6 \qquad \text{for } f'_c > 6000 \text{ psi} \qquad \text{(per ACI 363R-92}^{1}\text{)}$$

** Nonlinear fiber elements automatically account for cracking of concrete because the concrete fibers have zero tension stiffness.

Source: 2011 LATBSDC

Analysis Methods

- **Serviceability:**
  - ✓ Can use either
    1. Linear Response Spectrum Analyses
       - CQC mode combination
       - 90% mass participation
    2. Nonlinear Response History Analyses
- **For MCE (ultimate state) evaluation:**
  - ✓ Must use
    - Nonlinear Response History Analyses
- **Inherent torsional properties of the structural system should always be considered.**

P-Δ Inclusion

- **P-Δ effects must be included in all analyses**

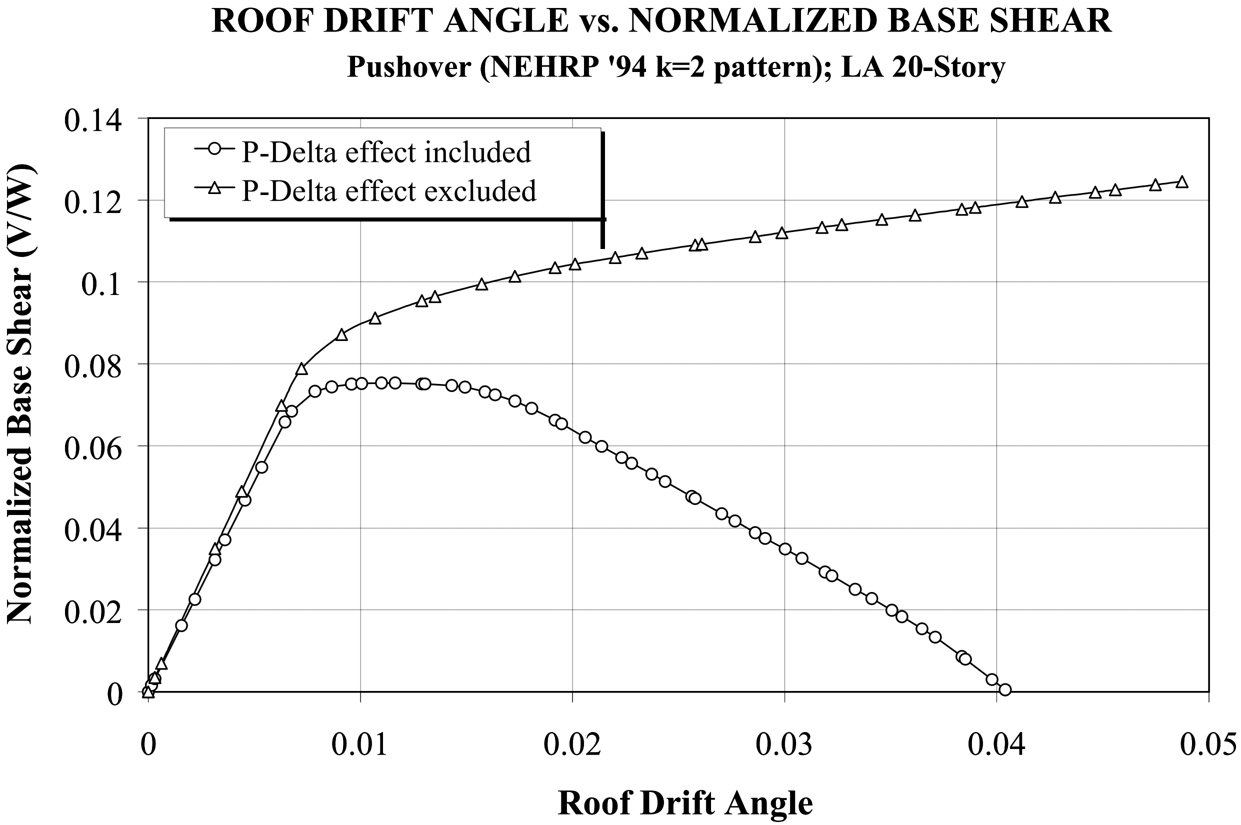


Figure courtesy of Prof. Helmut Krawinkler

Modeling Nonlinear Behavior

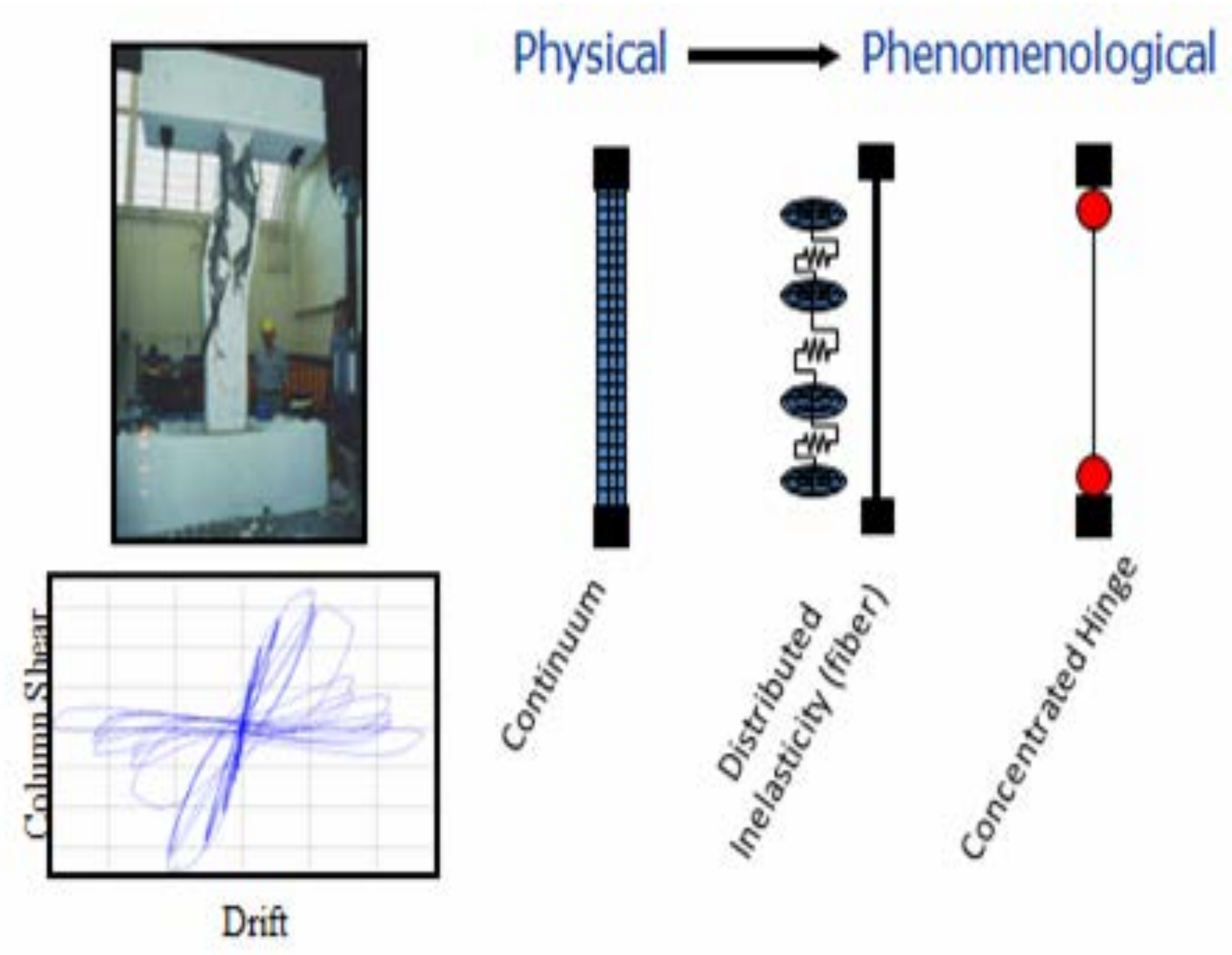


Figure courtesy of Prof. Prof. Greg Deierlein

Modeling Nonlinear Behavior

- **Concentrated plasticity model for beams and columns and fiber elements for walls are most common**
- **All other elements and components that in combination significantly contribute to or affect the total or local stiffness of the building should be included in the mathematical model.**
- **Axial deformation of gravity columns in a core-wall system is one example of effects that should be considered in the structural model of the building**

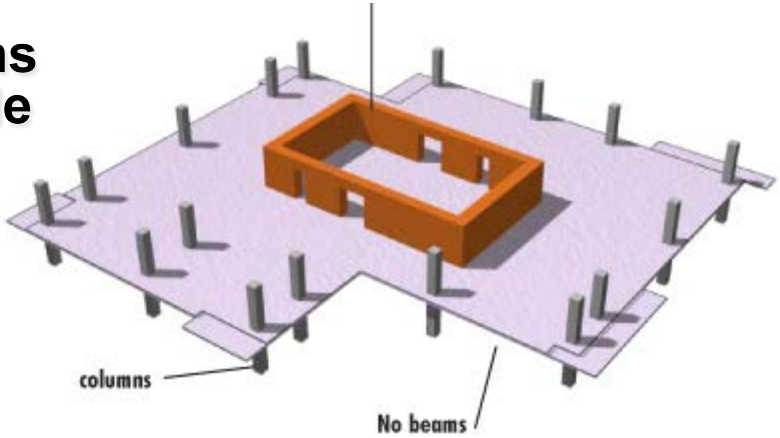


Figure courtesy of MKA

Accidental Eccentricity (AE)

- **2011 LATBSDC**
  - ✓ **Consider implications during serviceability evaluation**
  - ✓ **Address if significant during MCE evaluation**

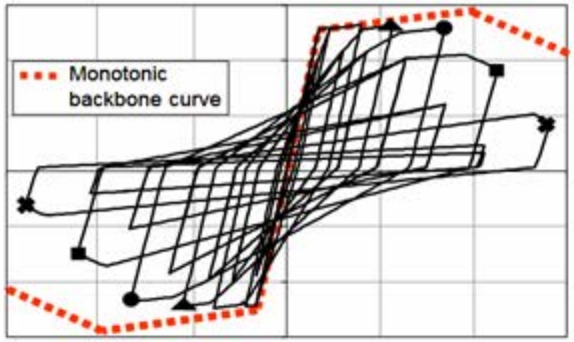
- **2010 PEER TBI**
  - ✓ **Do not need to consider**

- **Consideration of AE in nonlinear analyses requires multiple evaluations and little is gained by such time-consuming exercises.**

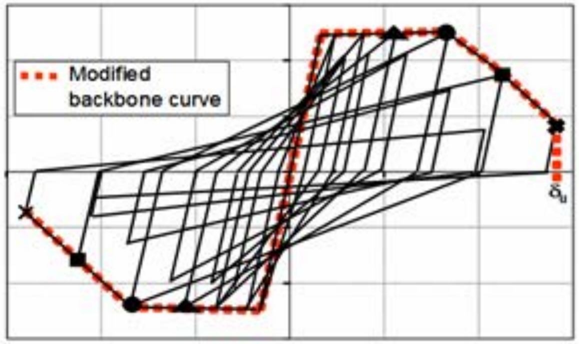
Modeling Strength / Stiffness Degradation

- **2010 PEER TBI**
  - ✓**Provides detailed guidelines on four approved methods for modeling degradation**
- **2011 LATBSDC**
  - ✓**Adopts the first two of the detailed procedures contained in 2010 PEER.**

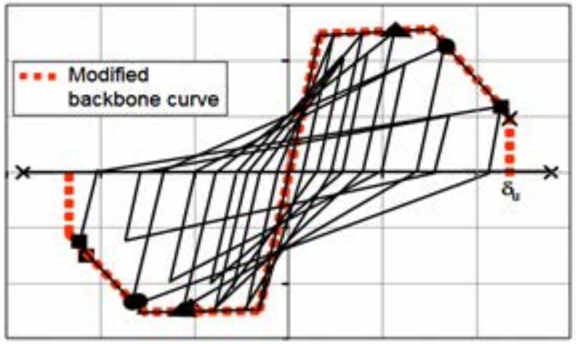
2010 PEER TBI Degradation Modeling Options



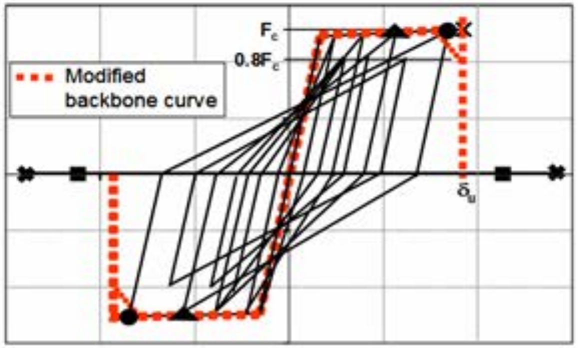
(a) Option 1 – with cyclic deterioration



b) Option 2 – modified backbone curve = envelope curve



(c) Option 3 - modified backbone curve = factored monotonic backbone curve



(d) Option 4 – no strength deterioration

Figure courtesy of Prof. Helmut Krawinkler

Upper Limit on Column Axial Forces

- **Large axial forces reduce available column ductility**

- **2011 LATBSDC**
  - ✓**MCE: $P \leq 0.4f'_cA_g$**

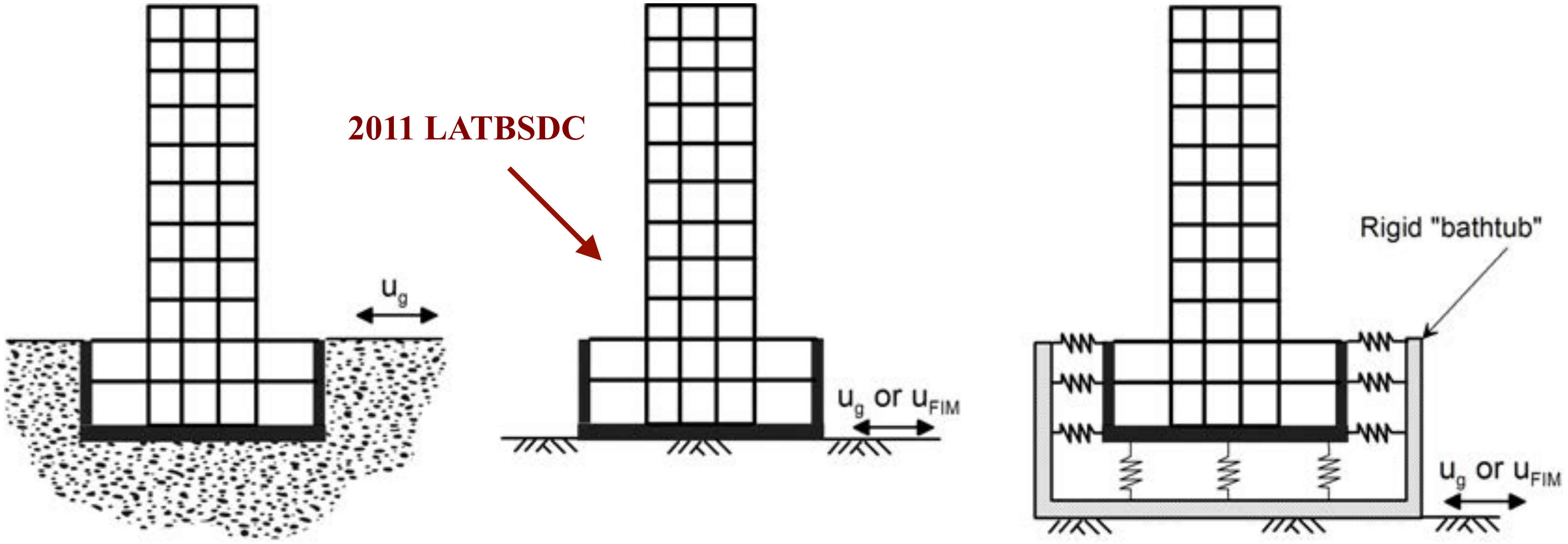
- **2010 PEER TBI**
  - ✓**MCE: P < balanced load**

    $\leq 0.3f'_cA_g$

Soil-Foundation-Structure-Interaction (SFSI)

- **Naeim & Stewart (2008) demonstrated the difficulties of realistic modeling of SFSI in a design environment.**
- **2010 PEER TBI has two recommended modeling techniques**
- **2011 LATBSDC recommends a single approach for this.**

2010 PEER TBI Suggested Modeling Techniques for SFSI



2011 LATBSDC

(a) Complete System

(b) Model for service-level earthquake

(c) Model for maximum-considered earthquake

Damping

- **A particularly thorny issue**
  - ✓ In nonlinear analyses most of the damping is represented by hysteretic behavior of the elements
  - ✓ Some small additional viscous damping may be justified for:
    - Energy dissipation provided by components and systems not explicitly modeled
    - As necessary to avoid numerical instability
- **2011 LATBSDC**
  - ✓ Limits viscous damping to 2.5% for both serviceability and MCE.
- **2010 PEER TBI**
  - ✓ 2.5% for linear serviceability evaluation
  - ✓ Refers to ATC-72 for nonlinear evaluation

Ground Motion Selection and Scaling

- A minimum of 7 pairs is usually required
- 2011 LATBSDC
  - ✓ Adopts by reference Chapter 21 of ASCE 7
- 2010 PEER TBI
  - ✓ More flexible
  - ✓ Permits scaling, matching or CMS
  - ✓ Multiple CMS required if CMS is used, making this impractical for tall buildings
- Most practicing engineers prefer matching
  - ✓ One must be careful as, matched motion contains less record to record dispersion

Acceptance Criteria -- Maximum Drift

- **Absolute Maximum Transient Drift Limit**
  - ✓**Serviceability:**
    - **2011 LATBSDC & 2010 PEER TBI:**

      0.005 overall
  - ✓ **MCE:**
    - **2011 LATBSDC & 2010 PEER TBI:**

      0.030 max average at any story

      0.045 max. interstory drift at any story under any record

Acceptance Criteria -- Maximum Drift

- **Absolute Maximum Residual Drift Limit**
  - ✓ **Serviceability:**
    - **2011 LATBSDC 0.005 overall**
  - ✓ **MCE:**
    - **2011 LATBSDC and 2010 PEER:**

      0.010 average max. of time histories

      0.015 maximum from any

Acceptance Criteria -- Serviceability

- **2011 LATBSDC**
  - ✓ **Brittle Actions:**

    Strength Demand $\leq$ 0.7*Capacity
  - ✓ **Ductile Actions:**
    - **Linear Analysis**

      Strength Demand $\leq$ 1.50 Capacity
    - **Nonlinear Analysis**

      Can use up to IO limit of ASCE 41

Acceptance Criteria
MCE

- 2010 PEER and 2011 LATBSDC
  - ✓ Ductile Actions:
    - Deformation Demand < ASCE 41-06 CP Deformation Capacity
    - Continuous Load Path
    - Capacity exhausted when it drops below 80% of maximum strength

Acceptance Criteria -- MCE

- 2010 PEER
  - ✓ Brittle Actions:
    - Two Groups:
      - Critical Actions
        - failure mode pose severe consequences to structural stability under gravity and/or lateral loads
        - Design for mean + 1.3 to 1.5 times SD
      - Noncritical Actions
        - Design for mean values
        - Use $\phi = 0.75$ for shear
- 2011 LATBSDC
  - ✓ Essentially the same, except uses 1.5 times mean and $\phi = 1.0$

R/C Specific Requirements

- **None in 2010 PEER**
- **Several in 2011 LATBSDC**
  - ✓**Detailing**
    - **The spacing limit of 12 inches of ACI 318 §21.5.3.2 (d) is reduced to 6 inches.**
  - ✓**High-Strength Concrete**

Peer Review Requirements

- Each project needs a Seismic Peer Review Panel (SPRP)
- SPRP is to provide an independent, objective, technical review of design
- Paid by the owner but reports to Building Official
- Responsibility for the structural design remains solely with the EOR
- SPRP is not a plan checking entity
- Minimum of three members with recognized expertise in relevant fields such as:
  - ✓ structural engineering
  - ✓ earthquake engineering research
  - ✓ performance-based earthquake engineering
  - ✓ nonlinear response history analysis
  - ✓ tall building design
  - ✓ earthquake ground motions, geotechnical engineering, geological engineering

Instrumentation Requirements

- **2010 PEER TBI**
  - ✓No requirements
- **2011 LATBSDC**
  - ✓Detailed requirements
  - ✓Consistent with CGS / CSMIP

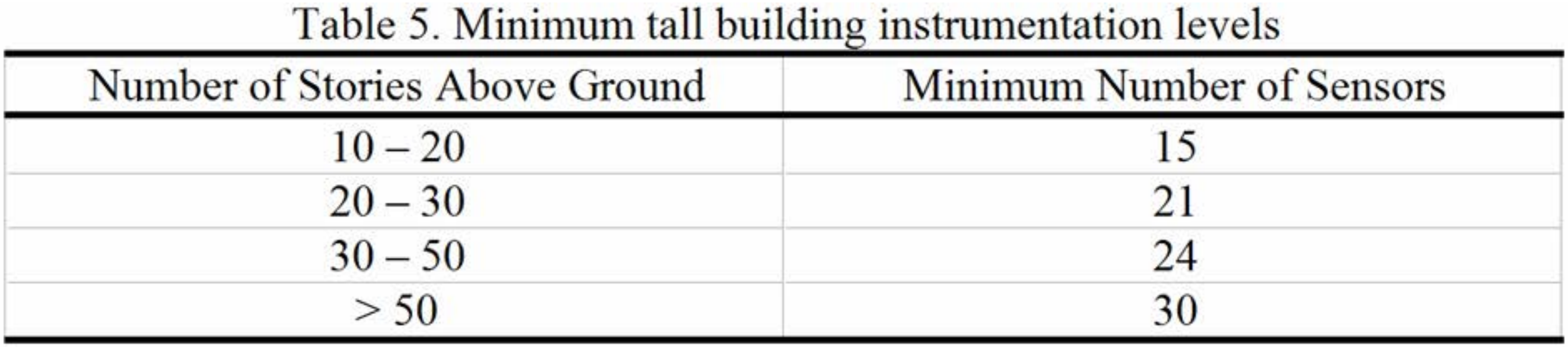


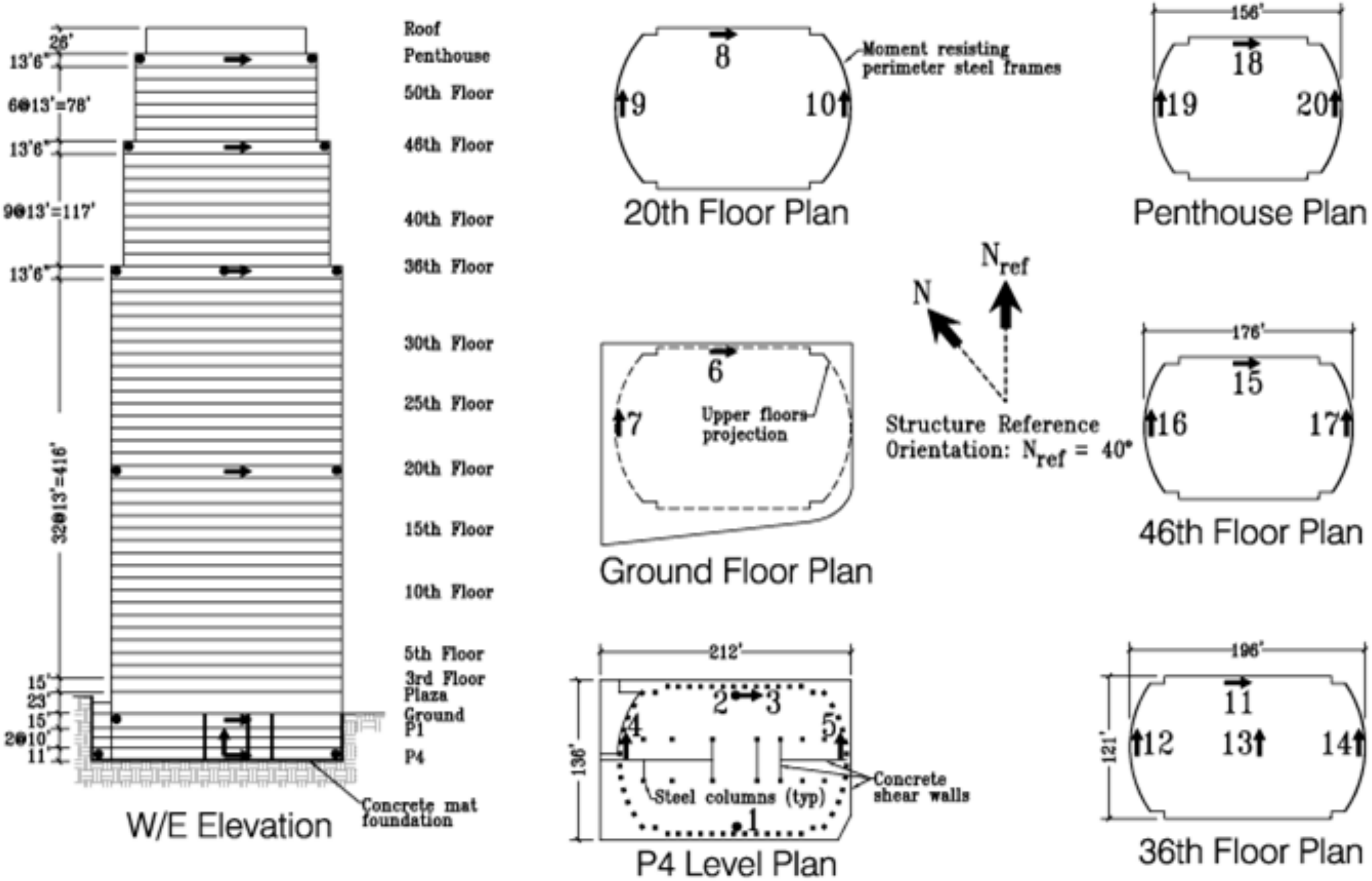
Table 5. Minimum tall building instrumentation levels

Number of Stories Above Ground	Minimum Number of Sensors
10 – 20	15
20 – 30	21
30 – 50	24
> 50	30

A typical tall building instrumented by CSMIP

Los Angeles - 54-story Office Bldg
(CSMIP Station No. 24629)

SENSOR LOCATIONS



CSMIP sensor layout

Applications

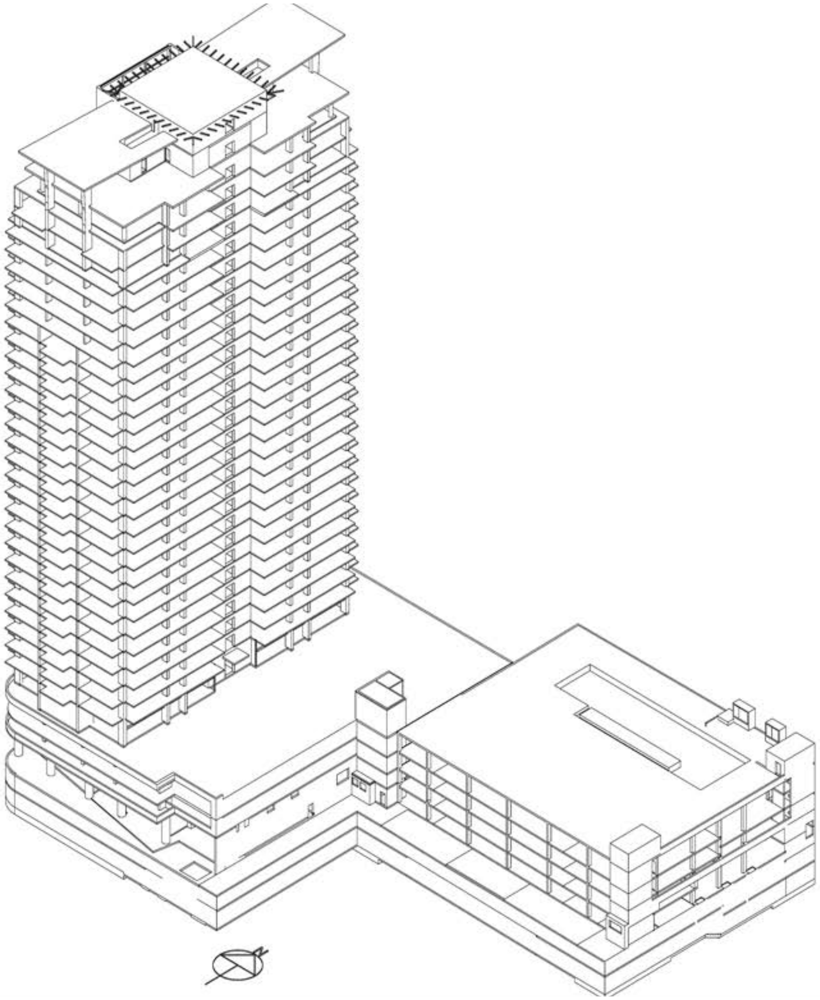
- Many tall buildings have been designed using these guidelines in Los Angeles, San Francisco, San Diego, and elsewhere
- Here are some examples

✓ Los Angeles:
  - 888 Olive
  - 1133 Olive
  - 1212 Flower Towers
  - Wilshire & Grand
  - Metropolis Tower

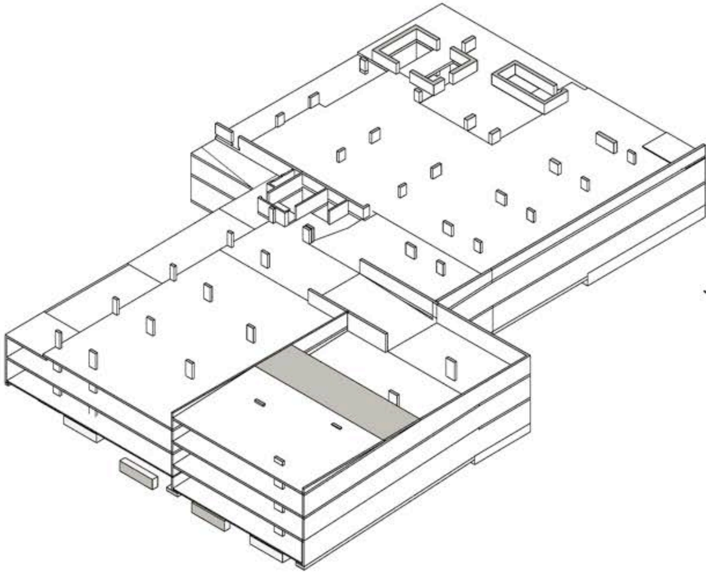
✓ San Diego
  - 7th & Ash

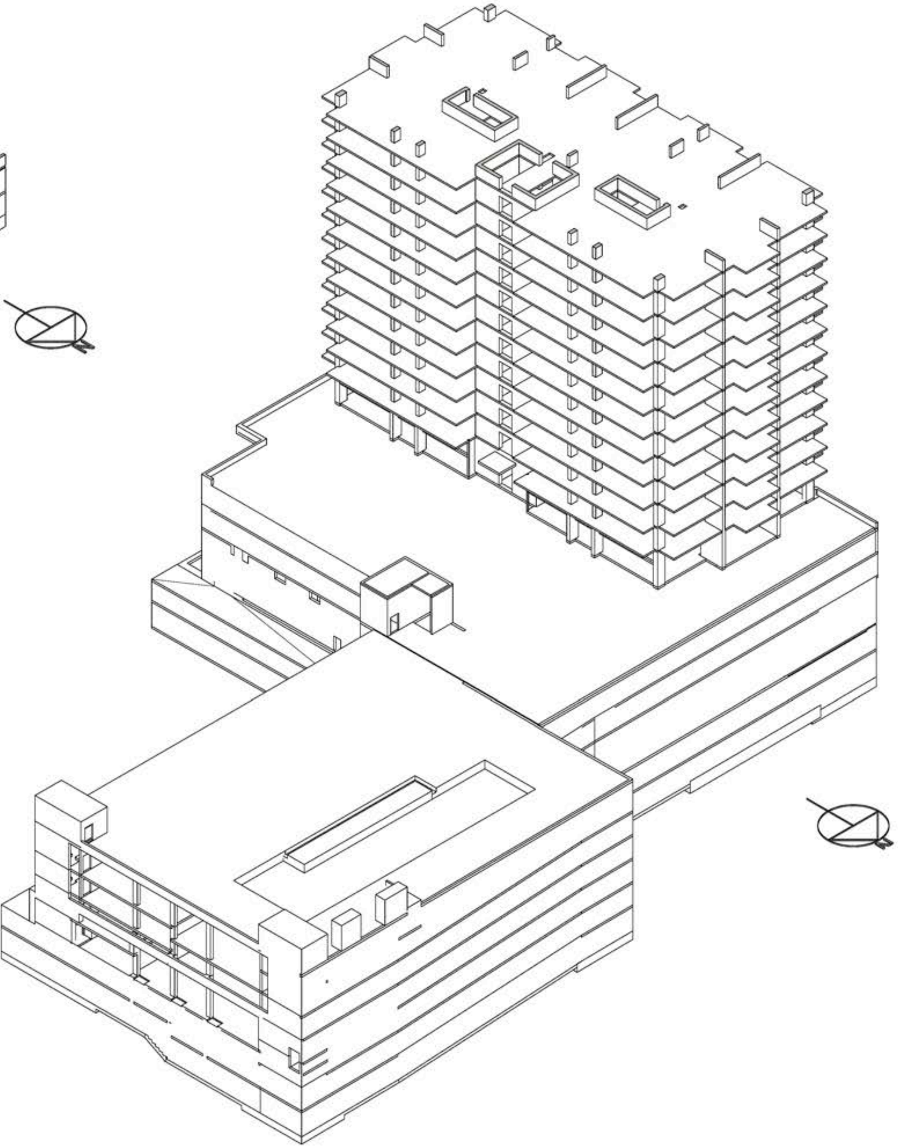
✓ San Francisco
  - Transbay Tower

- **888 Olive Street in downtown Los Angeles**
  - ✓ 34 stories
  - ✓ Core wall construction
  - ✓ Podium
  - ✓ Subterranean levels
  - ✓ Basement walls
  - ✓ Flat plates
  - ✓ Gravity columns



Illustrations and drawings courtesy of Onni Group and Glotman-Simpson





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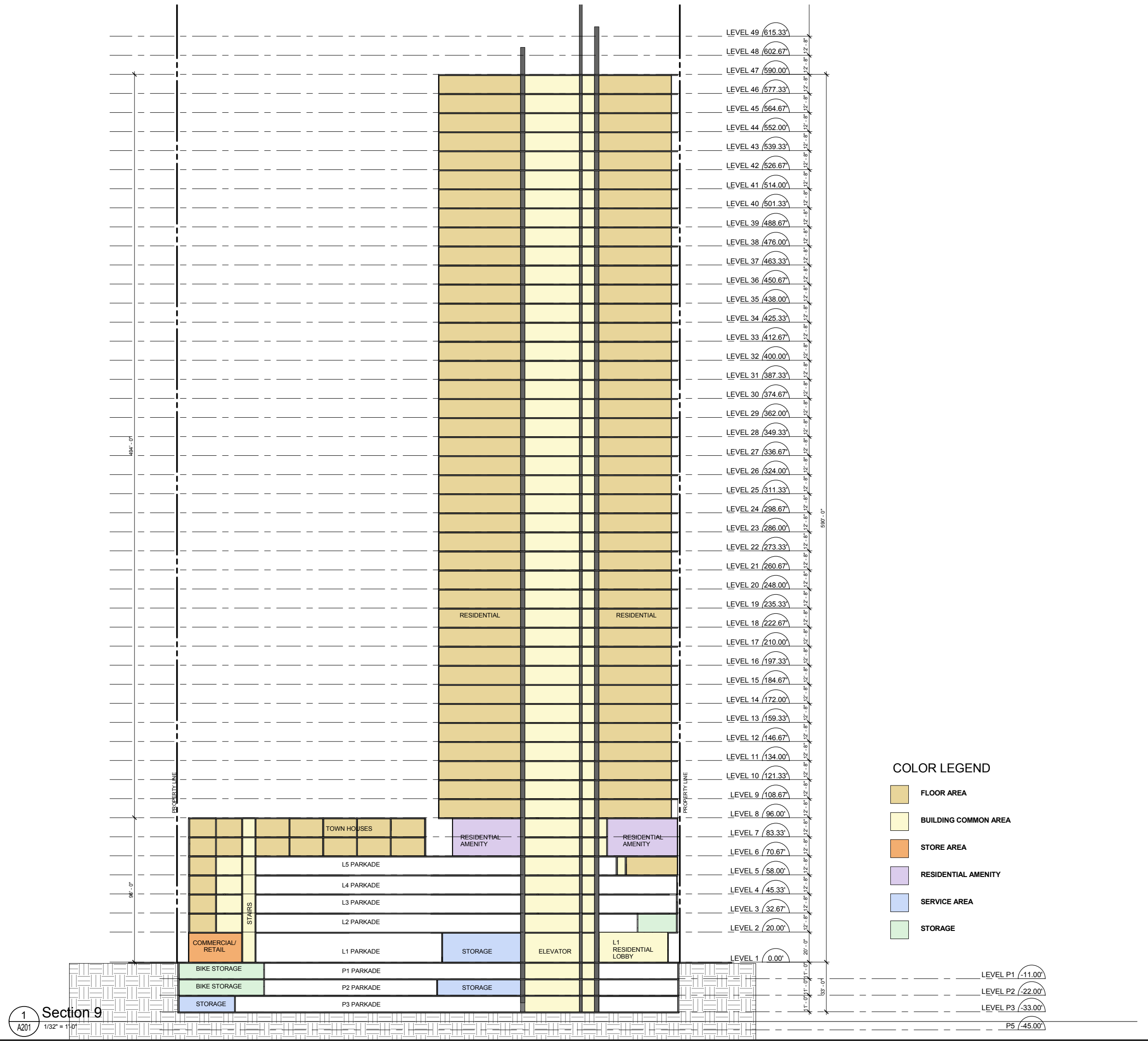


COLOR LEGEND

- FLOOR AREA
- BUILDING COMMON AREA
- STORE AREA
- RESIDENTIAL AMENITY
- SERVICE AREA
- STORAGE

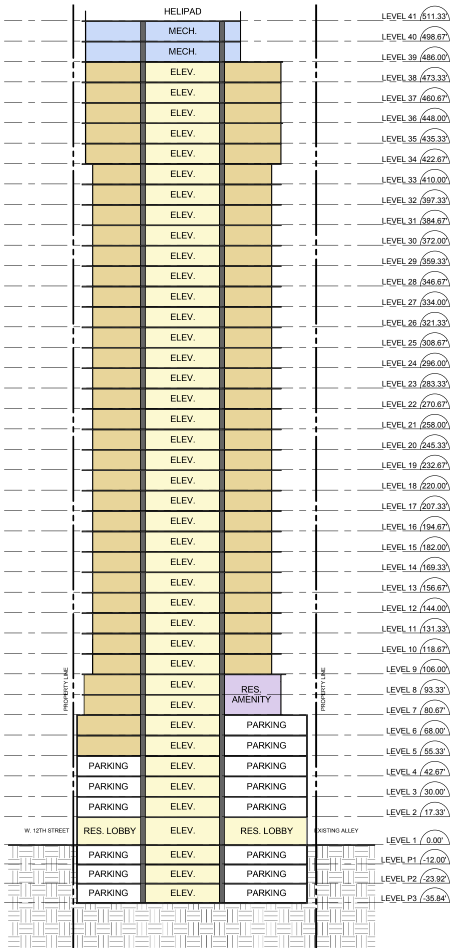
CHRIS DIKEAKOS
ARCHITECTS INC.

OLIVE ST. MIXED-USE DEVELOPMENT
817 - 825 Hill St. & 820 S. Olive St., Los Angeles, CA

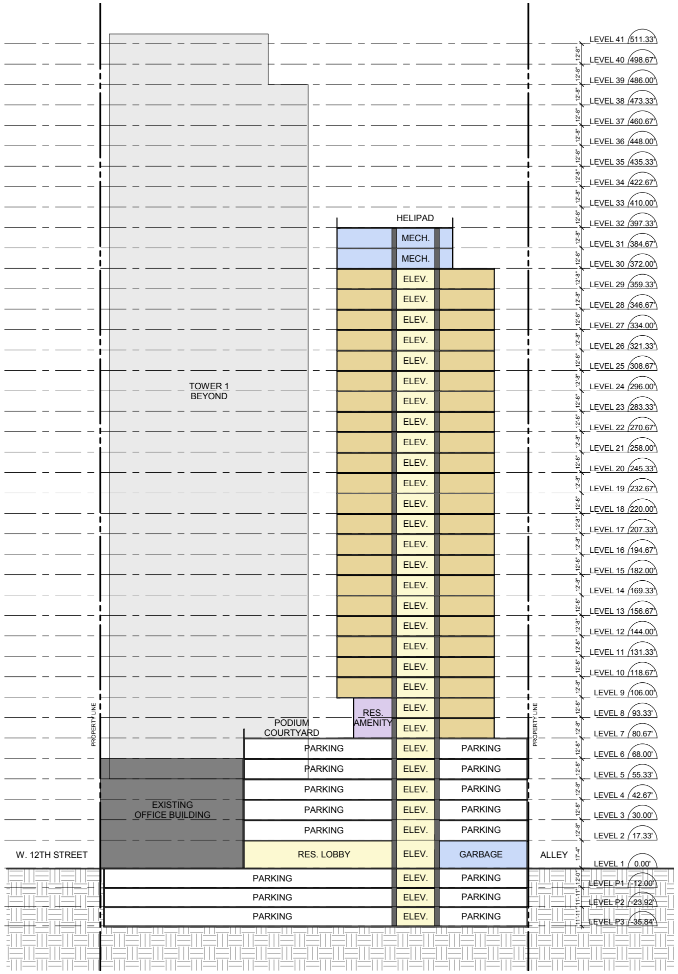
SECTION
SCALE: 1/32" = 1'-0"

Design Development
August 26th, 2013

A306



2
A201
TOWER 1 BUILDING SECTION
1/32" = 1'-0"



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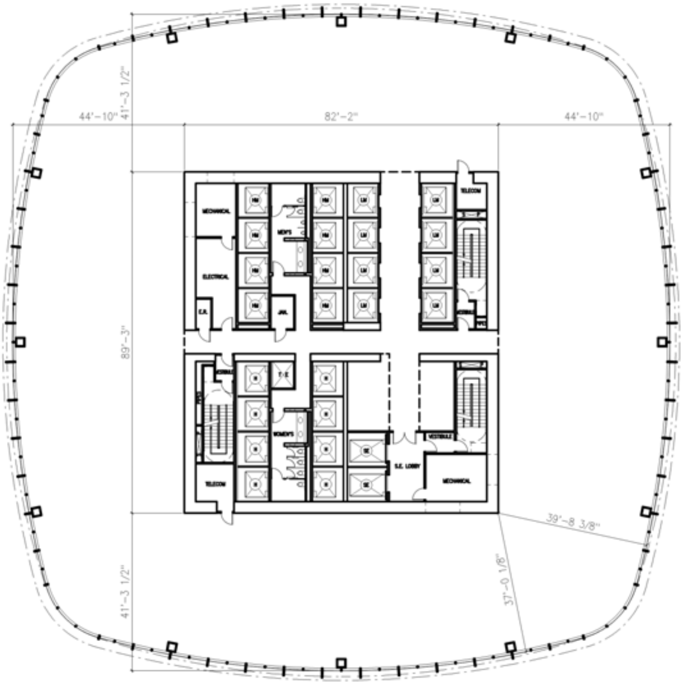
A201
TOWER 2 BUILDING SECTION
1/32" = 1'-0"

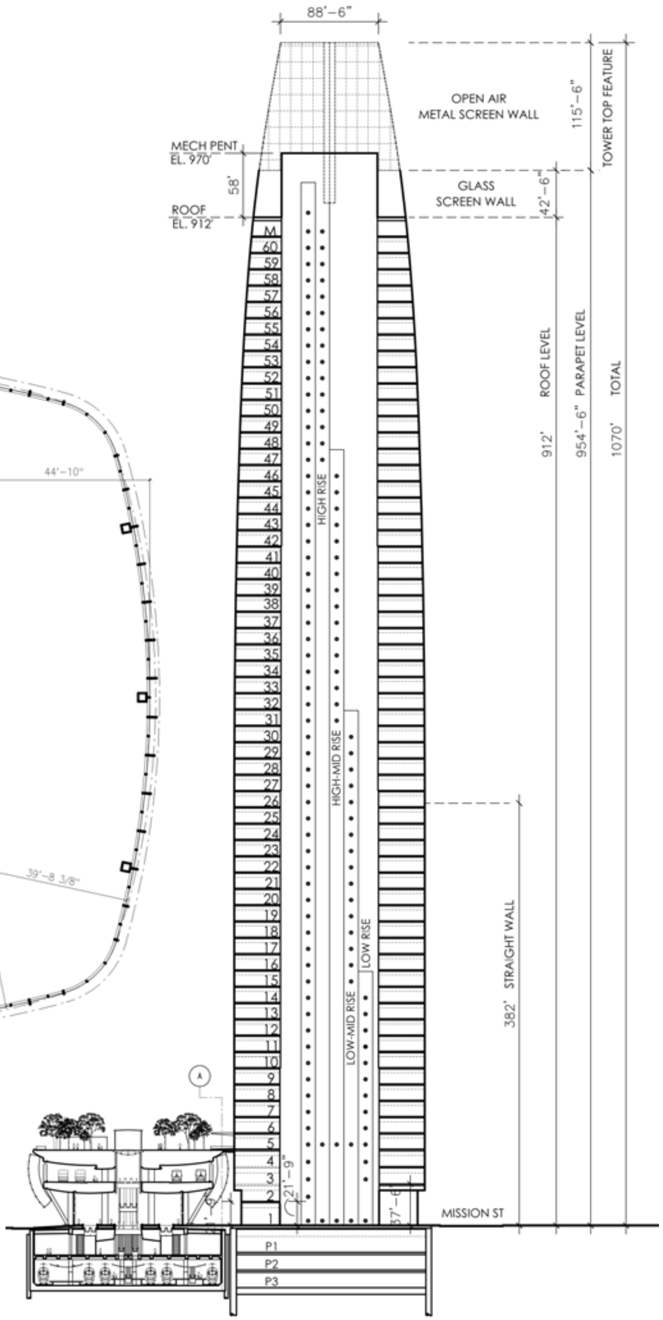
CHRIS DIKEAKOS
ARCHITECTS INC.

FLOWER ST. MIXED-USE DEVELOPMENT
1212 S. Flower Street, Los Angeles, CA

BUILDING SECTIONS
SCALE: 1/32" = 1'-0"

DESIGN DEVELOPMENT
August 26, 2013


44'-10"
82'-2"
44'-10"
41'-3 1/2"
89'-3"
41'-3 1/2"
MECHANICAL
ELECTRICAL
E.R.
JAN.
MEN'S
HM
LM
TELECOM
WOMEN'S
SE
S.E. LOBBY
VESTIBULE
MECHANICAL
TELECOM
39'-8 3/8"
37'-0 1/8"


88'-6"
OPEN AIR
METAL SCREEN WALL
115'-6"
TOWER TOP FEATURE
MECH PENT
EL. 970'
58'
ROOF
EL. 912'
GLASS
SCREEN WALL
42'-6"
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1
HIGH RISE
HIGH-MID RISE
LOW-MID RISE
LOW RISE
912' ROOF LEVEL
954'-6" PARAPET LEVEL
1070' TOTAL
382' STRAIGHT WALL
A
21'-9"
37'-6"
MISSION ST
P1
P2
P3

Thank you!