



# Seismic Design of High-rise Buildings

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# CTBUH Seismic Working Group

- Formed in early 2007
- Tasked with drafting international best practice recommendations for seismic design of high-rise buildings
- Lead authors
  - Willford, Whittaker, Klemencic
- Draft published in early 2008
- Review comments received in April 2008
- Final recommendations in August 2008

# CTBUH Working Group goals

- Review international best practice for analysis and design of high-rise buildings
  - Japan, China, USA
- Identify shortcomings in existing standards and codes vis-à-vis high-rise buildings
  - 1997 Uniform Building Code
  - ASCE7-05
  - 2006 International Building Code
- Draft internationally appropriate procedures for analysis and design across all regions of seismic hazard

# International practice

- Practices vary widely around the world
  - Alternate (or no) performance objectives
  - Use of unsuitable codes, standards, guidelines
  - Reliability (safety) of resultant designs unknown
- Traditional practice
  - 1997 UBC and derivatives
- Emerging practice
  - Performance-based design
    - Underpins CTBUH Recommendations
- Best practice in Japan and China

# Traditional practice

- 1997 Uniform Building Code and derivatives
  - Many permissible structural framing systems
    - None amenable to high-rise buildings
  - Minimum lateral seismic forces
    - No technical basis
  - Prescriptive rules
    - Developed for low- and medium-rise construction
  - Single level design (life safety +  $0.67 \cdot \text{MCE}$ )
  - No performance check

# Traditional practice

- Uniform Building Code
  - Building code based on SEAOC Blue Book
  - SEAOC Blue Book
    - USA West Coast practice
      - Low- and medium-rise buildings
    - First published in late 1950s
    - Four basic framing systems (78)
    - Three performance objectives
      - Single level check (life safety in rare earthquake)
    - Force-based design
    - Response modification factors

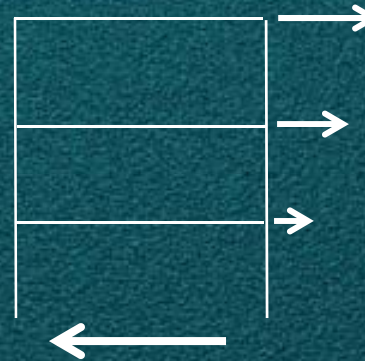
# Traditional practice

$$V = \frac{S_a(T, \xi)W}{R}$$

$$F_x = C_{vx} V$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^n w_i h_i^k}$$

$$\delta_i = C_d \delta_e$$



Framing system	R
<b>Steel</b>	
Special moment frames	8
Eccentrically braced frame (EBF)	7
Special concentrically braced frames	6
Moment frame (25%) and EBF	8
<b>Reinforced Concrete</b>	
Special moment frame	8
Special bearing shear walls	5
Moment frame (25%) and special shear wall	8

# Traditional practice

- 2003 NEHRP Recommended Provisions
  - 78 acceptable framing systems
  - Seismic design category E height limits
    - RC bearing walls, 49 m
    - Steel braced frames, 49 m
    - RC and steel moment frames (MFs), NL
    - Dual systems with special MFs, NL
- RC and steel MFs  $\neq$  tube construction
- Dual systems promoted for mid-rise buildings
  - Questionable performance at best

# Traditional practice

- Efficient framing systems in tall buildings
  - RC cores
  - RC, steel and composite perimeter tubes
  - RC cores, outriggers, perimeter columns
  - Steel braced cores and perimeter frames
- None of the above are permitted per codes, standards and guidelines
  - No technical basis to set aside these systems
  - No technical basis to accept permissible systems because performance is not proven

# Traditional practice

- High-rise buildings
  - Multiple modes of seismic response
    - Shears, moments
  - High gravity stresses
    - Cores and columns
    - Limited rotation capacity
  - Single value of R?
    - How computed?
    - Which mode?
  - Wind loadings



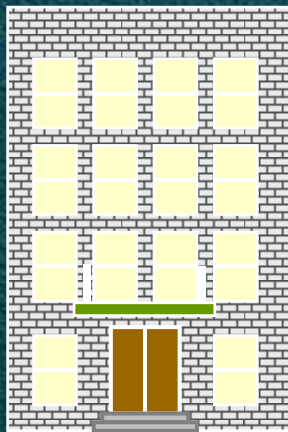
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# Emerging practice (USA)

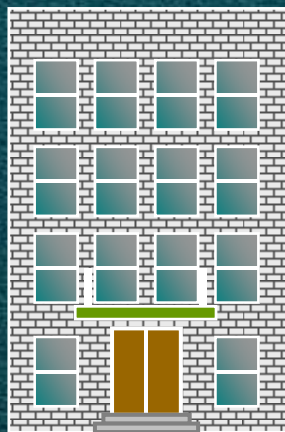
- Performance-based seismic design
  - Gen 1 and Gen 2 procedures
  - Multiple user-selected performance objectives
  - Design freedom
    - User-selected framing system and materials
  - Design burden
    - Detailed hazard (ground motion) computations
    - Nonlinear analysis
    - Component checking for deformations and forces
    - First principles mechanics for deformation capacity
  - Expert peer review

# Emerging practice (USA)

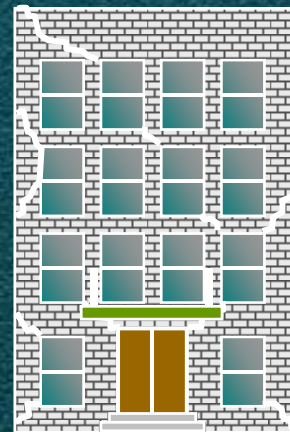
- Gen 1 performance-based eq engineering
  - FEMA 273 (97), FEMA 356 (00)
  - ASCE41 (06)



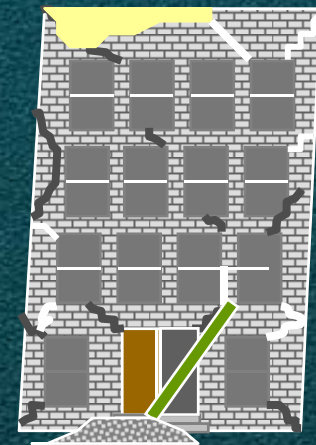
Operational



Immediate  
Occupancy

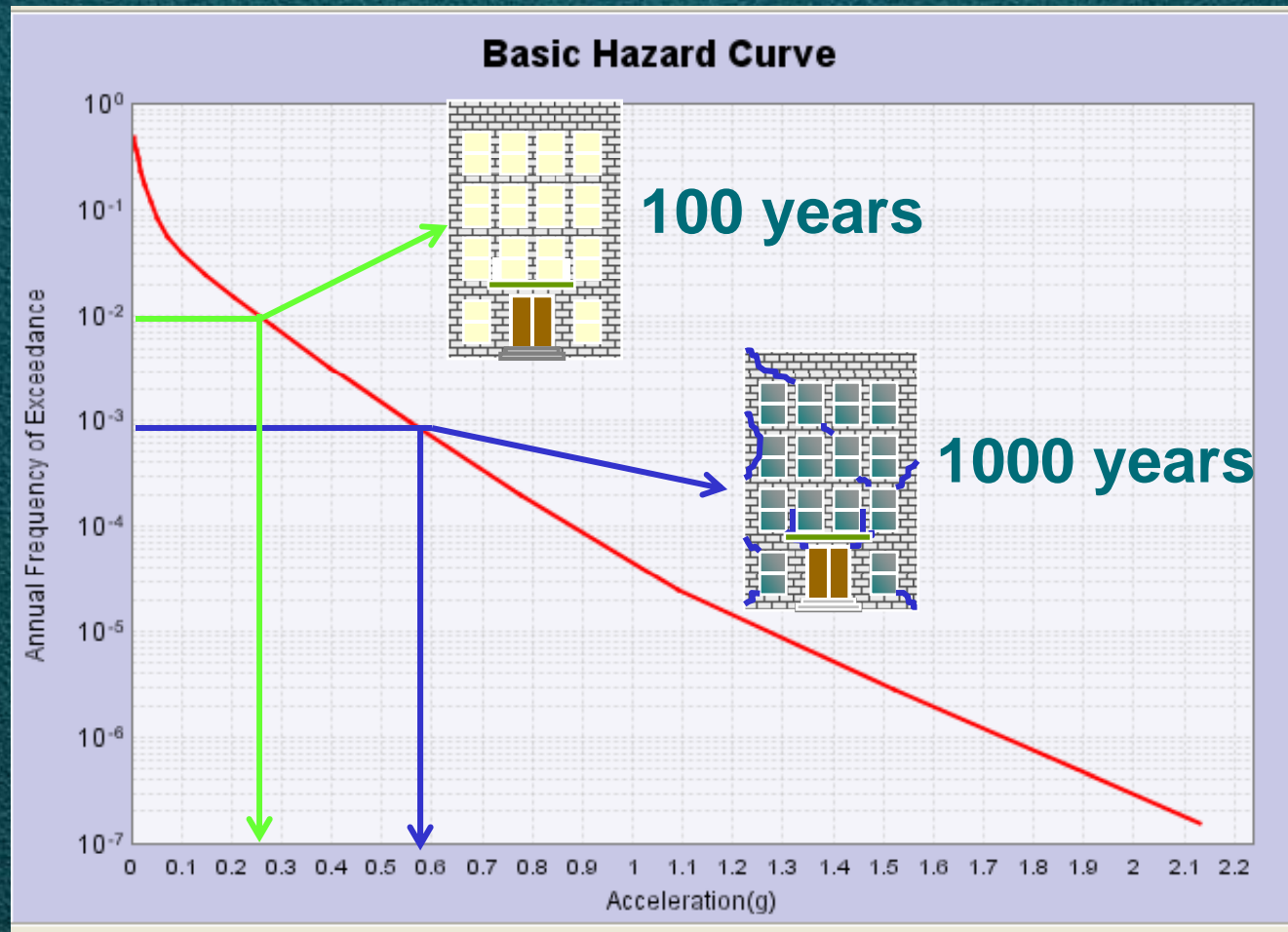


Life  
Safety

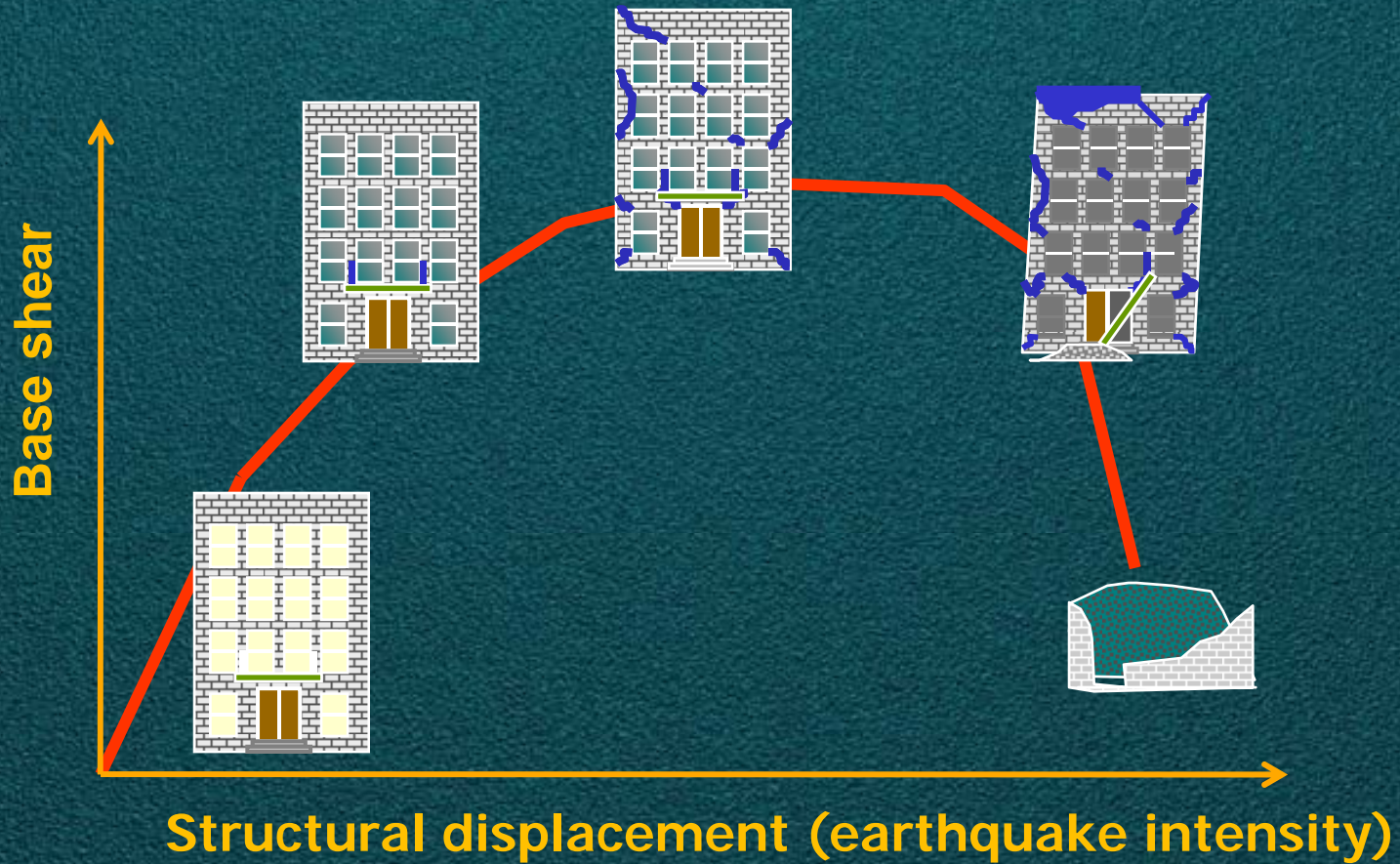


Collapse  
Prevention

# Emerging practice (USA)



# Emerging practice (USA)



# Emerging practice (USA)

- Gen 1 procedures
  - Backbone curves for component models
  - Nonlinear static analysis
    - First mode lateral load profiles
    - Appropriate for low- and mid-rise buildings
    - Inappropriate for high-rise buildings
      - Two or three modes contribute to response
- Gen 2 procedures (ATC-58 project)
  - Nonlinear response-history analysis
  - Appropriate selection and scaling of pairs of ground motions

# Best practice in Japan and China

- Performance based design
  - Japan since 1981
- Mandatory for buildings exceeding specified heights
  - 60 m in Japan
  - Depend on hazard and structural form in China
- User-specified framing systems and materials
- Multiple performance objectives
- Nonlinear response-history analysis
- Element ductility check

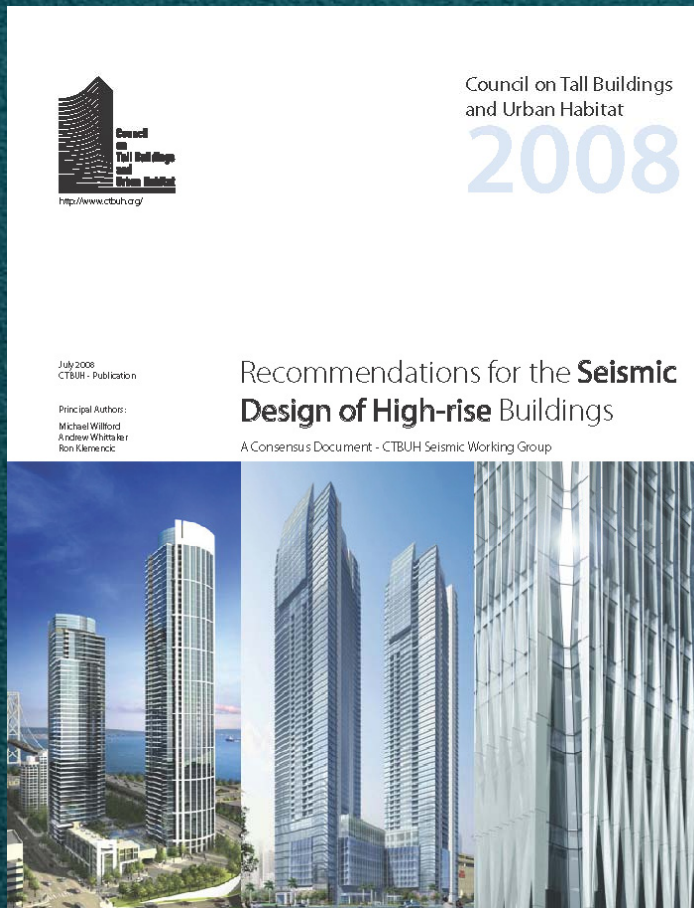
# Best practice in Japan

- Two performance objectives
  - No probability attached
  - Typically five ground motion sets per level
- Level 1: PGV = 25 cm/s (approx 0.25g PGA)
  - Design material strength
  - Elastic response required
  - Storey drift < 1:200
- Level 2: PGV = 50 cm/s (approx 0.5g PGA)
  - Expected material strength
  - Storey drift < 1:100
  - Storey ductility factor < 2
- Expert panel peer review

# Best practice in China

- Three performance objectives
- 50-year return period spectrum
  - Elastic response
- 475-year return period spectrum (10% in 50 yrs)
  - Repairable damage
  - Critical members to remain elastic
- 2475-year return period spectrum (2% in 50 yrs)
  - No collapse
  - Story drift limits
    - 1/50 to 1/120 depending on structural form
- Expert panel peer review

# CTBUH Recommendations



- Introduction and background
- Design objectives and philosophy
- Seismic hazard assessment
- Foundation effects
- Structural analysis and modeling procedures
- Energy dissipation
- References
- Appendices
  - Damping in tall buildings
  - Assessment in regions of low seismic hazard



# Design objectives and procedure

- Minimum design objectives
  - Service-level assessment
    - Negligible damage for spectral demands with a return period of about 50 years
    - No damage (elastic response) to structural and non-structural components
  - Collapse-level assessment
    - No collapse for spectral demands with a return period of 2475 years
    - Limit deformations for ductile actions and limit forces for non-ductile actions in structural components
    - Limit damage in those non-structural components whose failure might trigger building collapse



# Design objectives and procedure

- Seismic hazard analysis
  - Selection and scaling of pairs of ground motions
- 3D nonlinear building model
  - What to include?
  - How to model? ASCE-41 backbone curves?
- Perform nonlinear response-history analysis
  - Pairs of ground motions
- Assess results
  - Building deformations (drifts)
  - Component deformations (ductile actions)
  - Component forces (non-ductile actions)
- Link component response to system response
  - Major shortcoming of Gen 1 procedures



Council on Tall Buildings  
and Urban Habitat  
2008

Recommendations for the Seismic  
Design of High-rise Buildings  
A Consensus Document - CIBC's Seismic Working Group



# Design objectives and procedure

- Seismic design basis
  - Roadmap for analysis and design
    - Building description, description of seismic and wind resisting systems, performance objectives, seismic hazard results, wind study results, methods of analysis, modeling and acceptance criteria, drift criteria, criteria for nonstructural components
- Mandatory peer review
- Construction observation
- Instrumentation



# Seismic hazard assessment

- Probabilistic seismic hazard assessment
  - Family of seismic hazard curves
  - Maximum versus geomean demands
    - 2009 USGS seismic design maps
  - Near source effects and long period demands
- Site response analysis
- Selection and scaling of ground motions
  - No consensus on best procedures
  - #1: Matching to maximum spectrum (3x1)
  - #2: Matching to maximum and minimum spectra (3x2)
  - #3: Matching to maximum and minimum CMS (6x3)

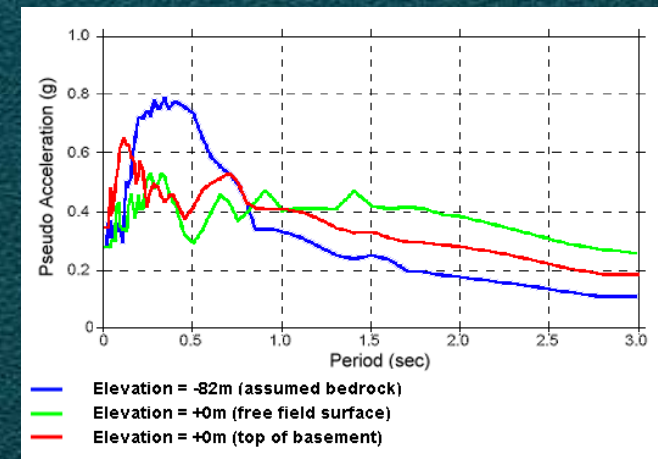
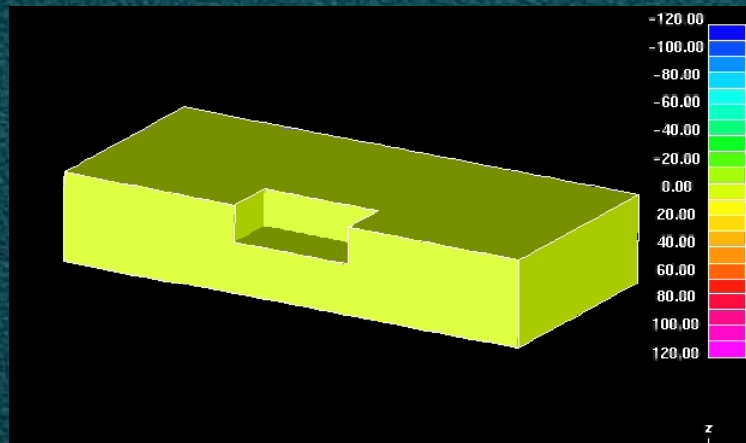


# Foundation effects

- Geotechnical parameters
  - Influence on earthquake shaking demands
  - Consider credible variations in soil properties
    - Bounding analysis
- Soil-foundation-structure interaction
  - Soil flexibility will influence the dynamic properties of the structure
  - Soil (material) and radiation damping
  - Foundation size (kinematic interaction)
- Modeling
  - Indirect models using equivalent linear springs
  - Explicit nonlinear soil models

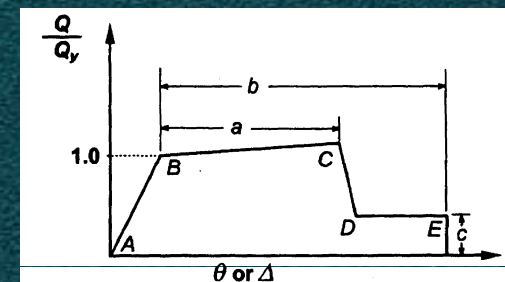
# Foundation effects

- Foundation embedment
  - Seismic input at underside of basement
  - Difference between basement and free-field motions
    - Greatest when surface soils are weak and soft



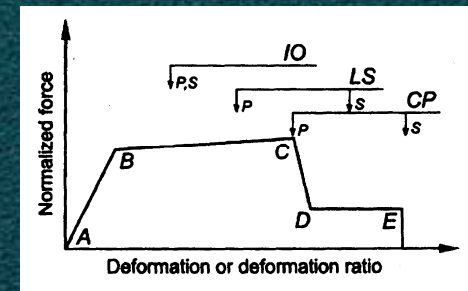
# Structural analysis and modeling

- Analysis procedures
  - Service-level: response spectrum
  - Collapse-level: nonlinear response history
- Capacity-design approaches
- Building models
  - Components that contribute strength and stiffness
  - Reactive mass
  - Component force-deformation relationships
    - Lumped plasticity models
      - ASCE41 if appropriate
    - Fiber models



# Structural analysis and modeling

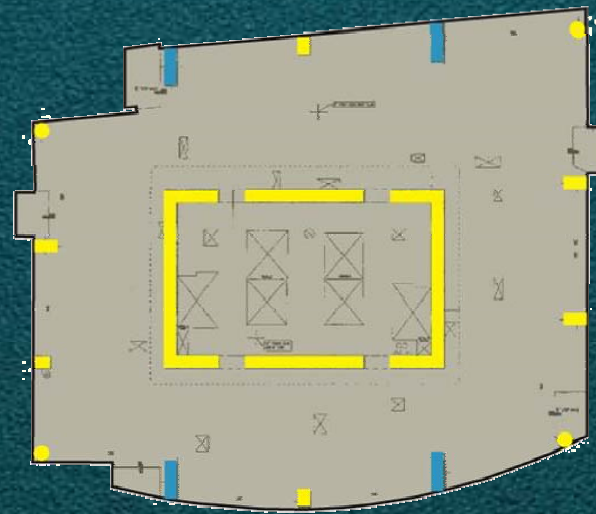
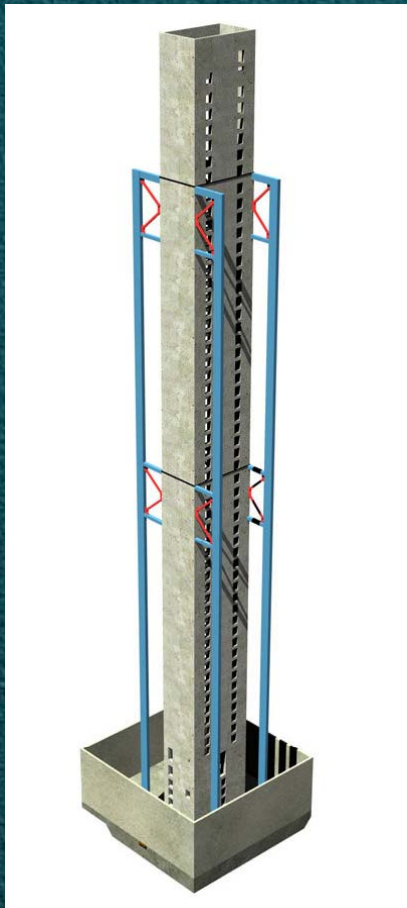
- Damping
  - Viscous (pre-yield) versus hysteretic (post-yield)
- Response-spectrum analysis
  - CQC method to combine the modes
  - Apply (Max, Min) or (100, 30 Max)
  - Maximum component response for assessment
- Nonlinear response-history analysis
  - Pairs of ground motions for analysis
  - Assessment at every time step
    - Coexisting forces and deformations
  - Deformation capacities in lumped plasticity models
    - ASCE41 or first principles
  - Deformation capacities in fiber models
  - Force capacities



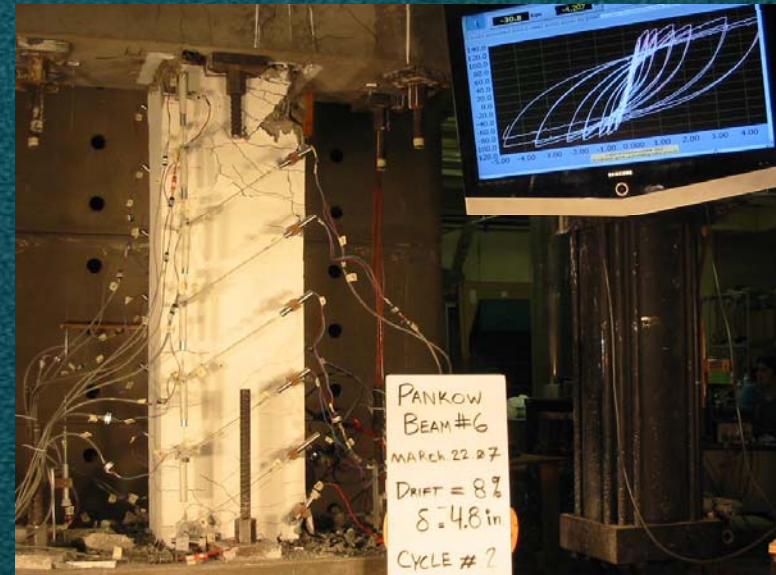
# Examples of PBD of high-rise buildings



# One Rincon Hill, San Francisco (MKA)



# One Rincon Hill, San Francisco (MKA)



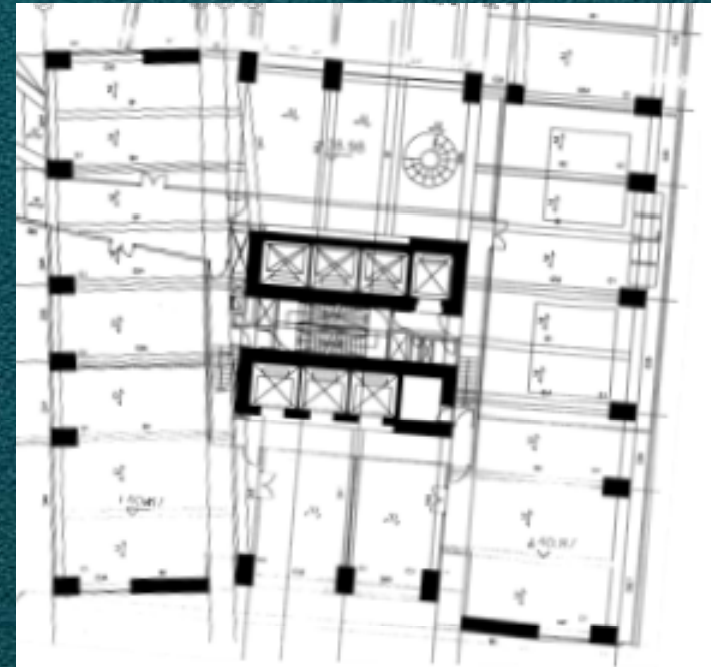
# St. Francis Towers, Manila (Arup)

- 60 storey RC building
- 3 km from active fault
  - M 7.5
- Super typhoons
- $T_1 = 6$  seconds
- 1997 UBC seismic design
  - $V \geq 0.05W$
  - Dual system required



# St. Francis Towers, Manila (Arup)

- 1997 UBC design
  - Dual system
    - Feasible?
    - Sensible?
  - High gravity stress in core and columns
    - Maximize floor space
    - Relative shortening
  - Only solution is a bearing wall
    - But not permitted

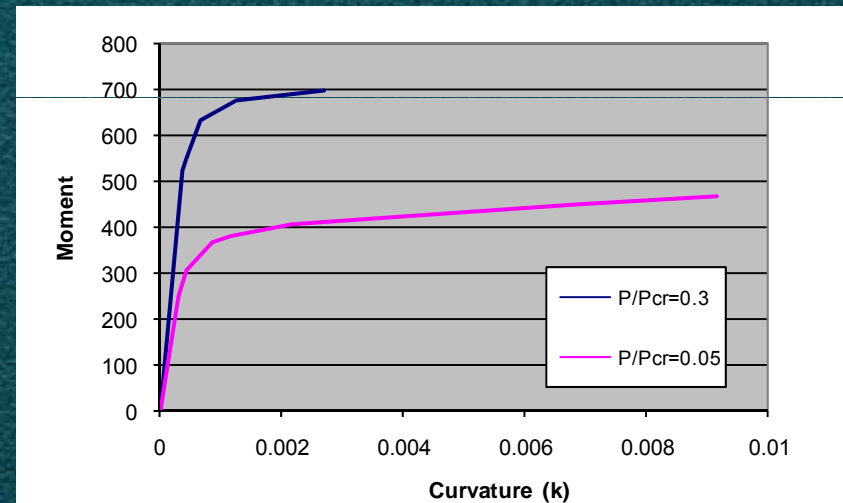


# St. Francis Towers, Manila (Arup)

- 1997 Uniform Building Code set aside
- Performance-based solution
  - Probabilistic seismic hazard analysis
    - Pairs of spectrally matched ground motions
  - Core walls only (no dual system)
  - Damped outriggers to achieve  $\xi = 0.07$
  - Lateral strength to resist wind loads
  - Nonlinear response-history analysis
  - Component checking
    - ASCE41 and first principles mechanics

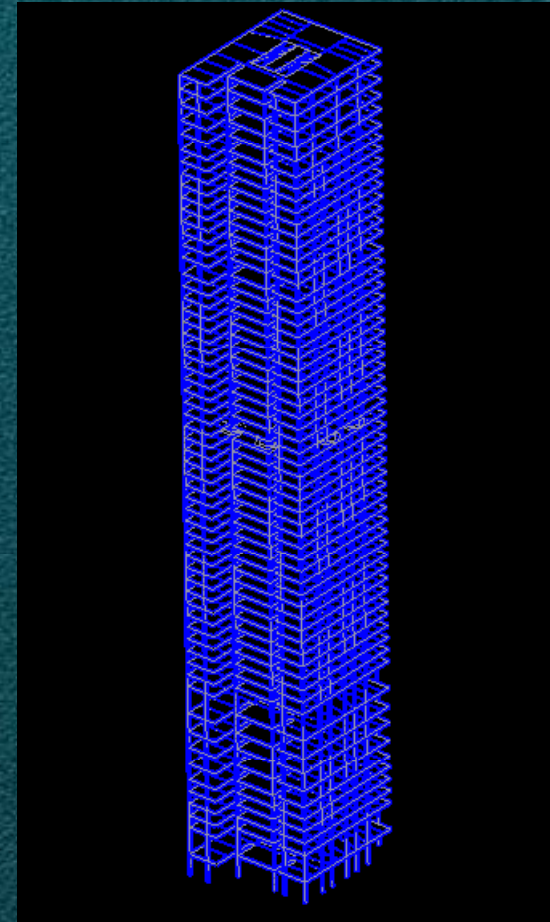
# St. Francis Towers, Manila (Arup)

- Core analysis
  - Low axial load
    - $\phi = 0.009$
    - $M_u/M_y = 1.25$
    - $\Theta_p = 0.05$
  - High axial load
    - $\phi = 0.003$
    - $M_u/M_y = 1.08$
    - $\Theta_p = 0.005$



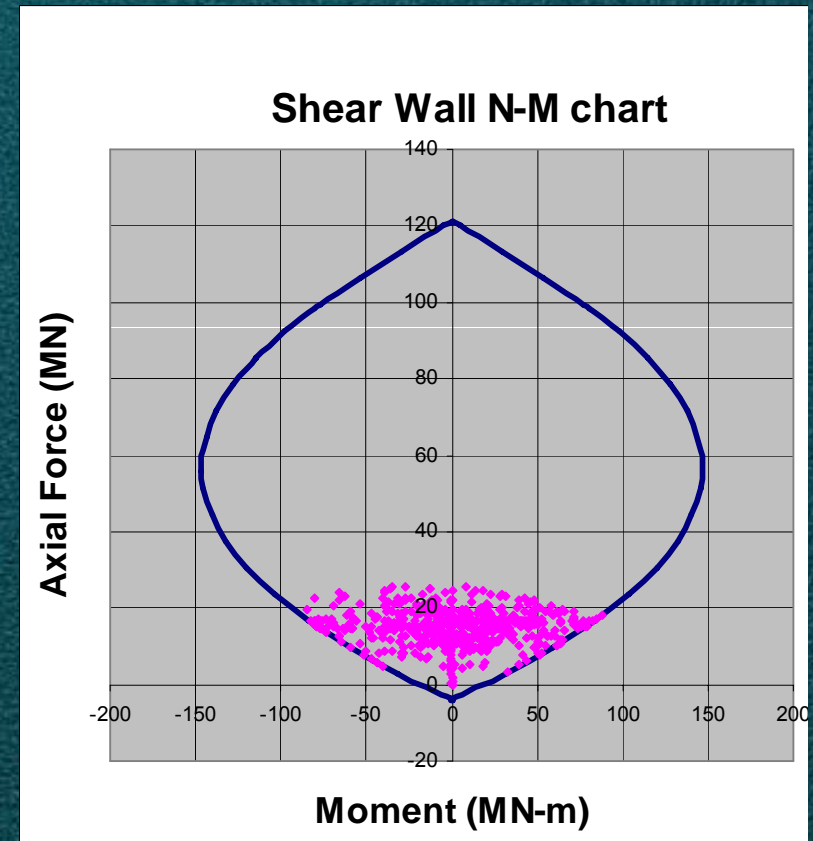
# St. Francis Towers, Manila (Arup)

- Nonlinear building model in LS-DYNA
- Nonlinear response history analysis
  - 2475-year spectrum
  - Pairs of motions
- Yielding in cores and columns at base
- Shears at base in excess of UBC



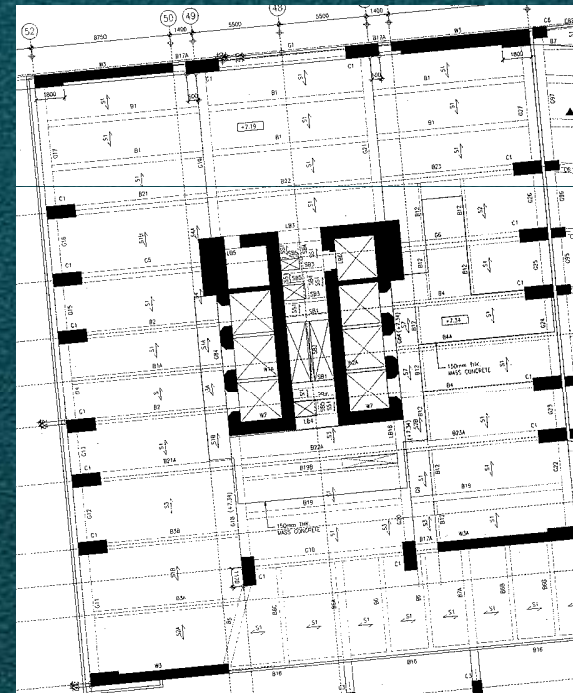
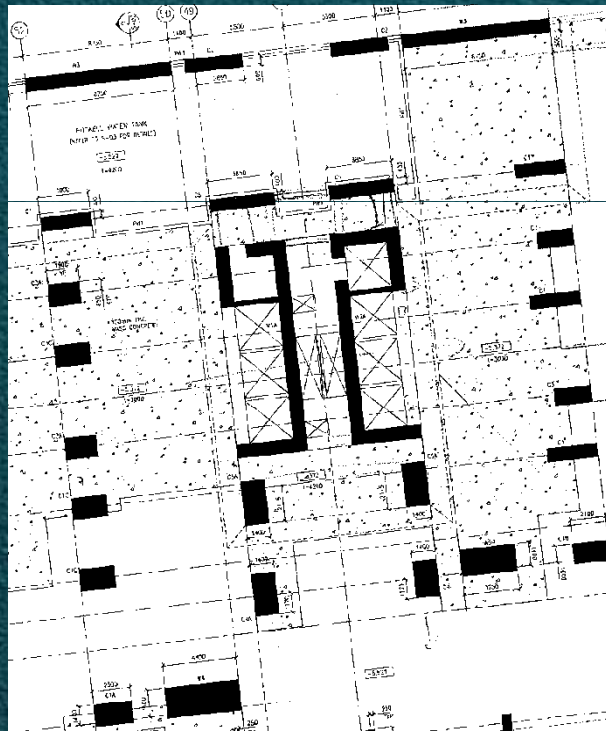
# St. Francis Towers, Manila (Arup)

- Core wall checking
  - Each time step
  - Rotation capacity varies as a function of (P,M)
    - First principles analysis
  - Shear strength computed using capacity principles
    - Reserve strength

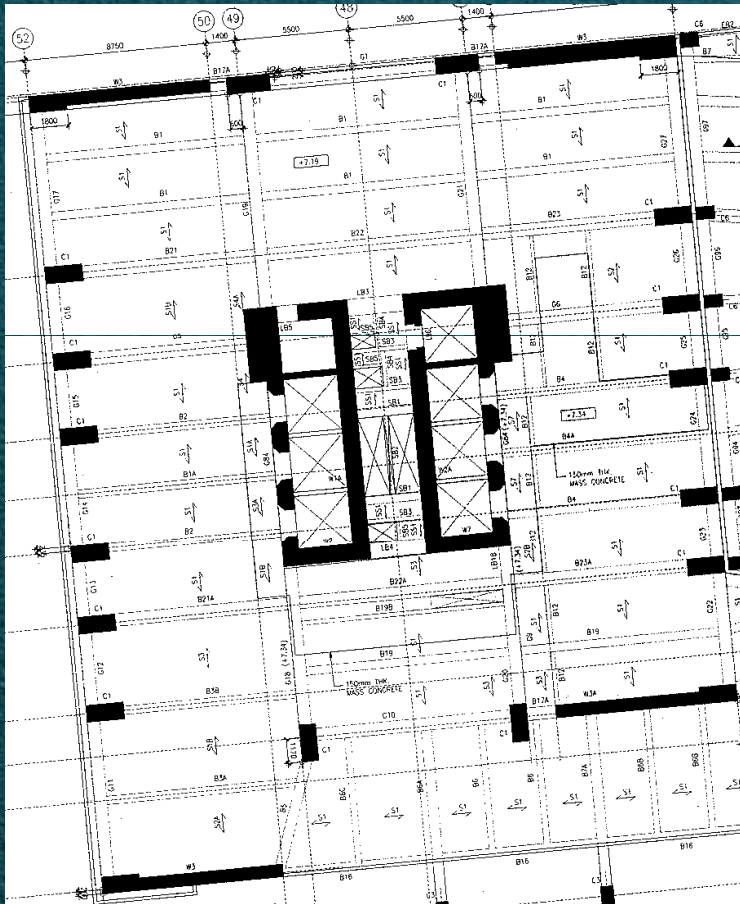


# St. Francis Towers, Manila (Arup)

- 1997 UBC
- Performance-based



# St. Francis Towers, Manila (Arup)



- Performance-based design
  - 30% reduction in concrete (core, column)
  - 40% reduction in rebar (core, column)
  - \$10+M USD savings
  - Higher shears at base
    - UBC unconservative
  - Known performance

# The Future Holds .....

- Application of Gen 2 PBD procedures to tall buildings
  - Risk based procedures such as
    - 10% probability of collapse/2475 year shaking
    - MAF of collapse = 0.0001
- Development of innovative structural, architectural and mechanical systems that are damage tolerant
- An update to the CTBUH Recommendations as knowledge is gained



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Chairman  
Council on Tall Buildings  
and Urban Habitat  
Michael Wilford  
Principal Architect  
Michael Wilford  
Architects

### Recommendations for the Seismic Design of High-rise Buildings

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