1

Performance-Based Design
Current Approaches & Future Trends

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2

Performance-Based Design—What?

An approach to obtain:

- Buildings that perform better than prescriptively design
- Buildings that don't meet code, but can be shown to be equivalent to prescriptively-designed buildings

Research Breakthroughs

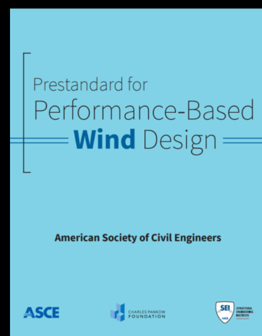
SEISMIC

WIND

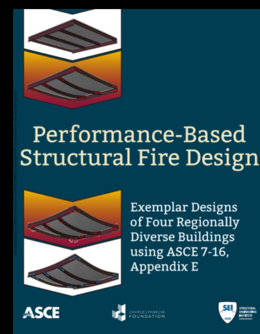
FIRE

Design Breakthroughs

SEISMIC



WIND



FIRE

Performance-Based Seismic Design

- ASCE 7-16 Tables 1.3-2 and 1.3-3
  - Performance objective → low likelihood of system collapse when subjected to the *Risk-targeted Maximum Considered Earthquake (MCE_R)* shaking

Table 1.3-2 Target Reliability (Conditional Probability of Failure) for Structural Stability Caused by Earthquake

Risk Category	Conditional Probability of Failure Caused by the MCE_R Shaking Hazard (%)
I & II	10
III	5
IV	2.5

Table 1.3-3 Target Reliability (Conditional Probability of Failure) for Ordinary Noncritical Structural Members Caused by Earthquake

Risk Category	Conditional Probability of Component or Anchorage Failure Caused by the MCE_R Shaking Hazard (%)
I & II	25
III	15
IV	9

Performance-Based Wind Design

- **ASCE 7-16 Table 1.3-1**
  - **Performance objectives for members and connections**

Table 1.3-1 Target Reliability (Annual Probability of Failure, P_F) and Associated Reliability Indices (β)[1] for Load Conditions That Do Not Include Earthquake, Tsunami, or Extraordinary Events[2]

	Risk Category			
Basis	**I**	**II**	**III**	**IV**
Failure that is not sudden and does not lead to widespread progression of damage	$P_F = 1.25 \times 10^{-4}$/yr $\beta = 2.5$	$P_F = 3.0 \times 10^{-5}$/yr $\beta = 3.0$	$P_F = 1.25 \times 10^{-5}$/yr $\beta = 3.25$	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$
Failure that is either sudden or leads to widespread progression of damage	$P_F = 3.0 \times 10^{-5}$/yr $\beta = 3.0$	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$	$P_F = 2.0 \times 10^{-6}$/yr $\beta = 3.75$	$P_F = 7.0 \times 10^{-7}$/yr $\beta = 4.0$
Failure that is sudden and results in widespread progression of damage	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$	$P_F = 7.0 \times 10^{-7}$/yr $\beta = 4.0$	$P_F = 2.5 \times 10^{-7}$/yr $\beta = 4.25$	$P_F = 1.0 \times 10^{-7}$/yr $\beta = 4.5$

[1]The target reliability indices are provided for a 50-year reference period, and the probabilities of failure have been annualized. The equations presented in Section 2.3.6 are based on reliability indices for 50 years because the load combination requirements in Section 2.3.2 are based on the maximum loads for the 50-year reference period.
[2]Commentary to Section 2.5 includes references to publications that describe the historic development of these target reliabilities.

Performance-Based Fire Design

- **ASCE 7-22 Table 1.3-5**
  - **Based on a conditional reliability of system assessment of ASCE 7 load combinations 2.5-1 and 2.5-2***
  - **Conditioned on occurrence of extraordinary event (uncontrolled fire)**
    - *However, the probability of the design event must be derived (Fire → NFPA 557 standard)*

Table 1.3-5 Target Reliability (Conditional Probability of Failure) for Structural Strength and Stability Limit States Caused by Extraordinary Load Events

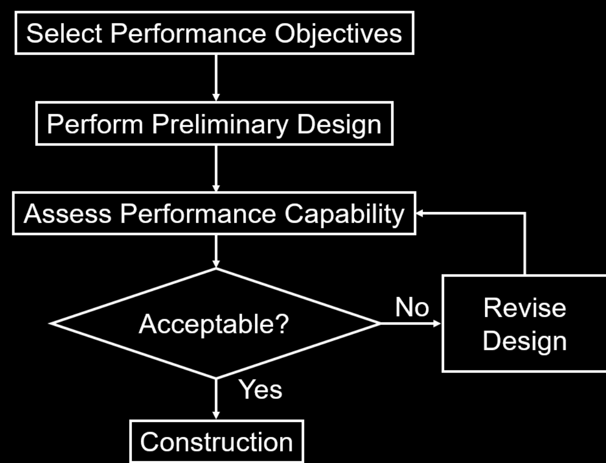
Risk Category	Conditional Limit State Probability	Design Fuel Load (Fractile)**
I	0.15	85%
II	0.10	90%
III	0.05	95%
IV	0.02	98%

*Ellingwood, B.R. (2007). "Acceptable Risk Bases." Chapter 2 in Best Practices for Reducing the Potential for Progressive Collapse in Buildings (Editors: Duthinh and Lew), NISTIR 7396, National Institute of Standards and Technology, Gaithersburg, MD 20899 pp. 5-26

***Each conditional probability involves the convolution of load/resistance; however, the uncertainly of structural action due to fire (load) is much higher than temperature-dependent material strength/stiffness. Hence, considering load exclusively is conservative and the "error" is very small*

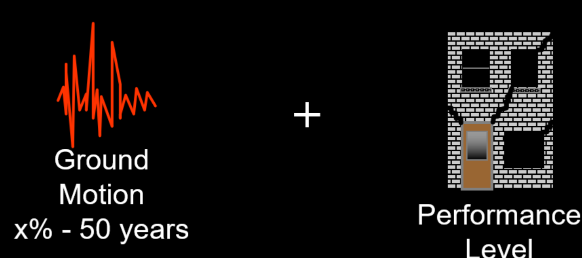
Performance-Based Seismic Design—What?

The PBSD Process



Performance-Based Seismic Design—What?

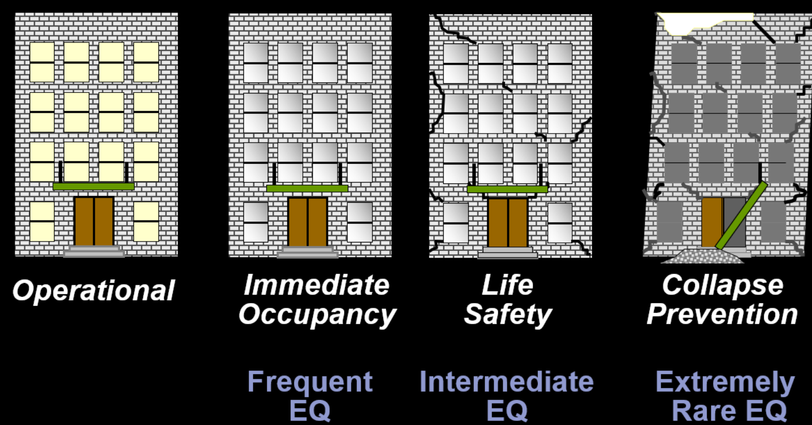
Performance Objectives



- **Design Hazard (earthquake ground shaking)**
- **Acceptable Performance Level (maximum acceptable damage, given that shaking occurs**

Performance-Based Seismic Design—What?

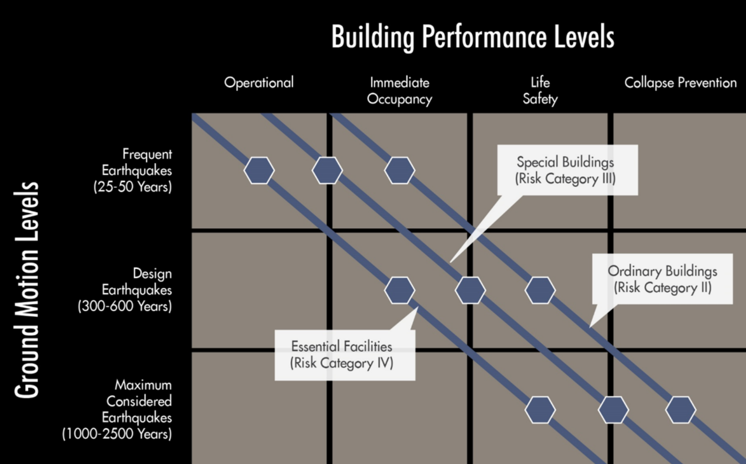
Performance Levels



11

Performance-Based Seismic Design—What?

Building Seismic Performance Matrix



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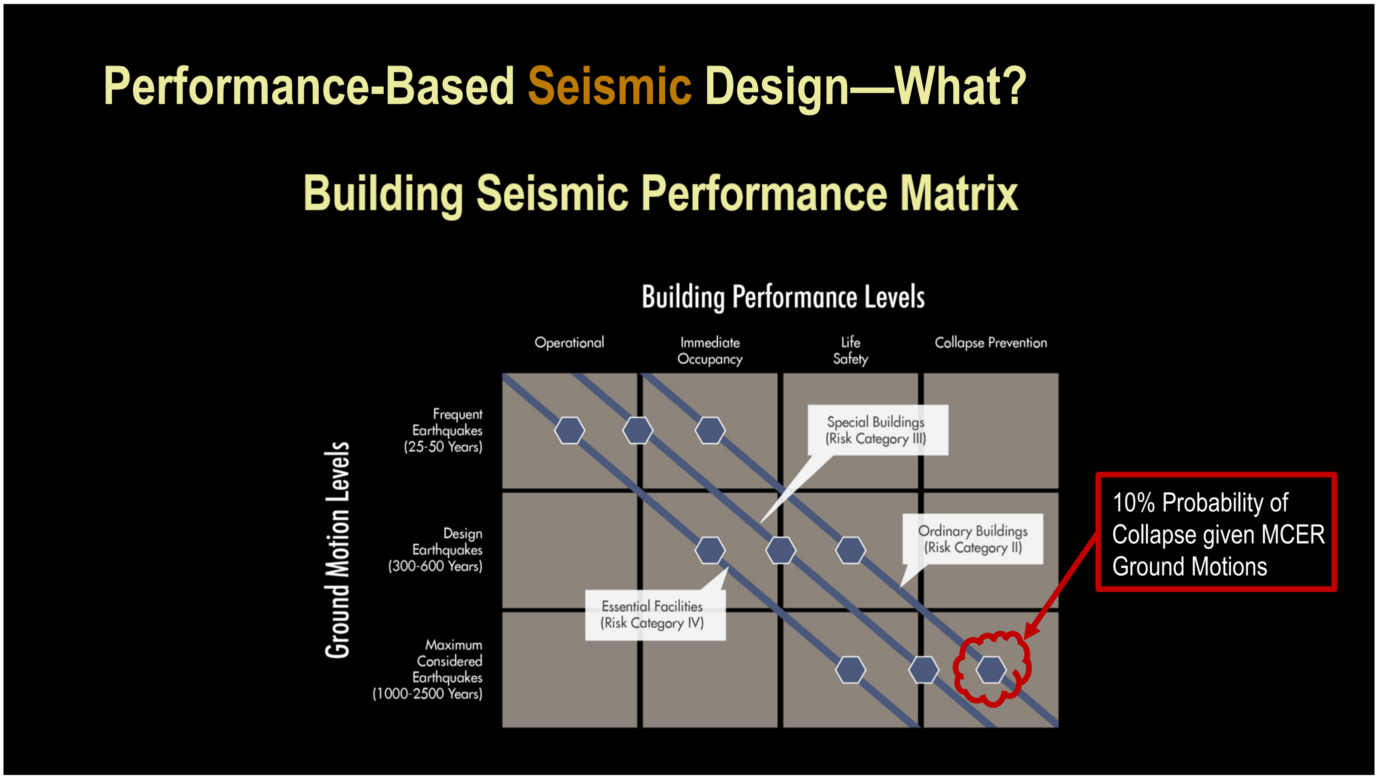
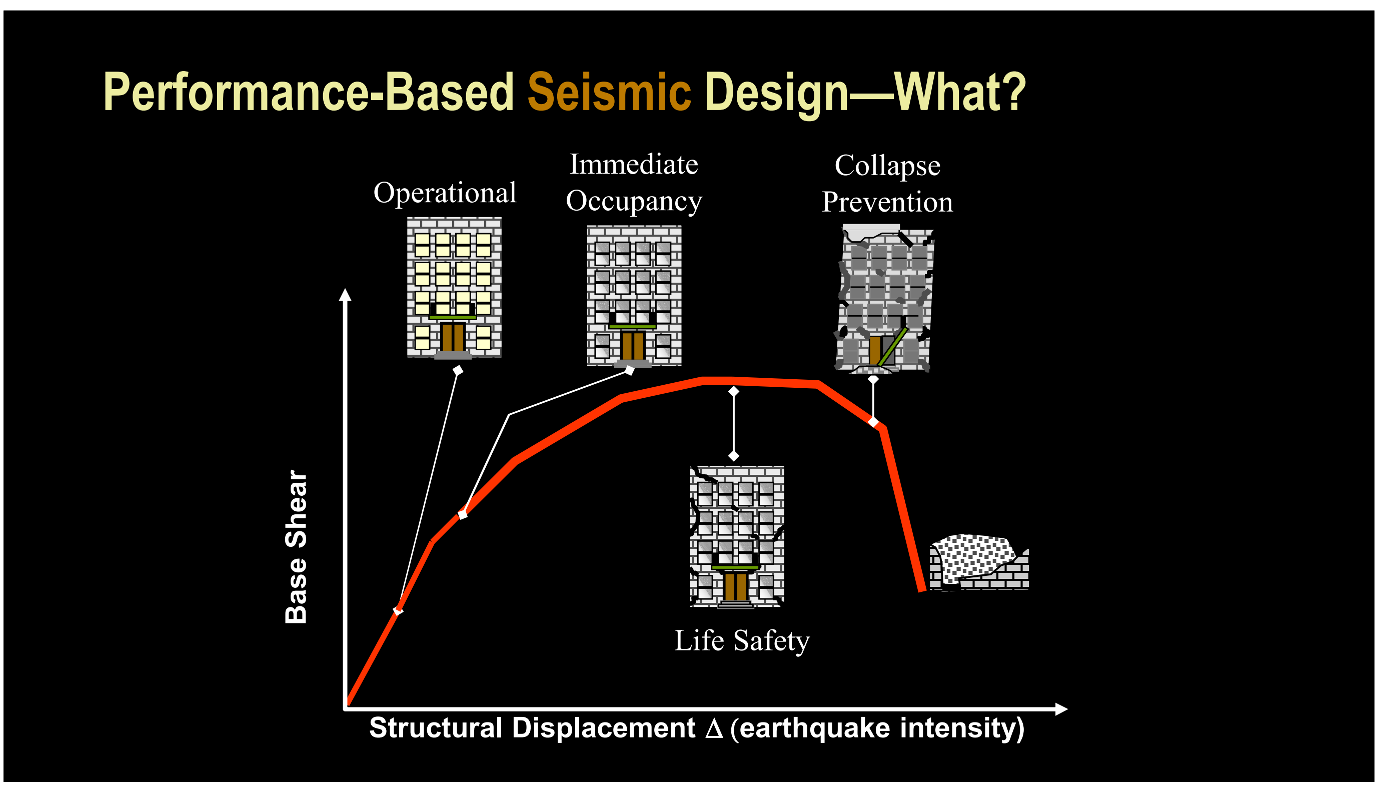
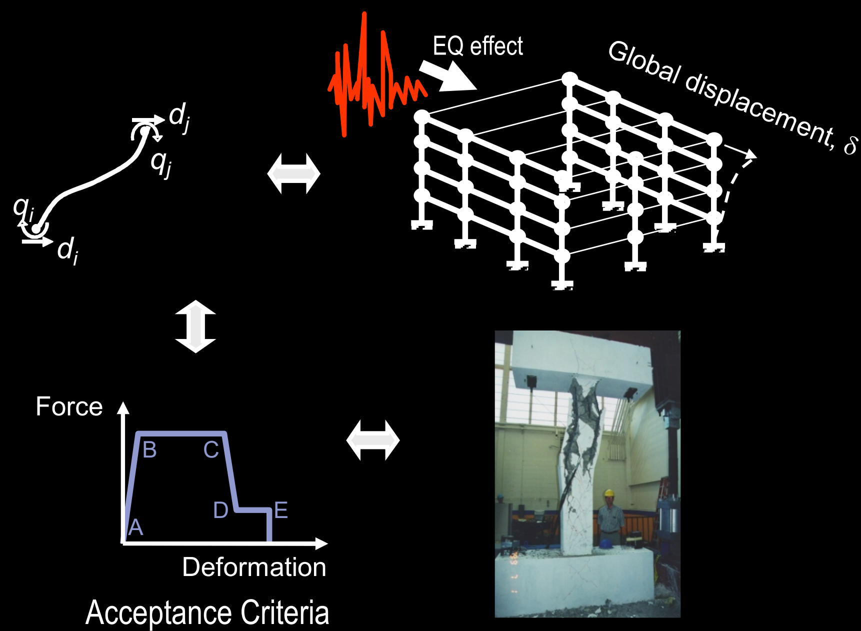

Performance-Based Seismic Design—What?
Building Seismic Performance Matrix
Building Performance Levels
Operational
Immediate Occupancy
Life Safety
Collapse Prevention
Ground Motion Levels
Frequent Earthquakes (25-50 Years)
Design Earthquakes (300-600 Years)
Maximum Considered Earthquakes (1000-2500 Years)
Special Buildings (Risk Category III)
Ordinary Buildings (Risk Category II)
Essential Facilities (Risk Category IV)
10% Probability of Collapse given MCER Ground Motions

13


Performance-Based Seismic Design—What?
Operational
Immediate Occupancy
Collapse Prevention
Life Safety
Base Shear
Structural Displacement Δ (earthquake intensity)

14

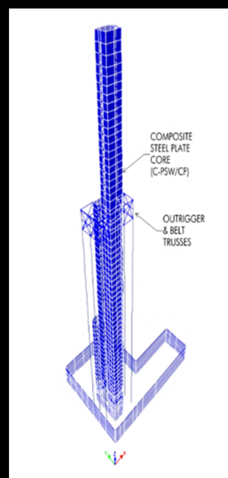
Performance-Based Seismic Design—What?

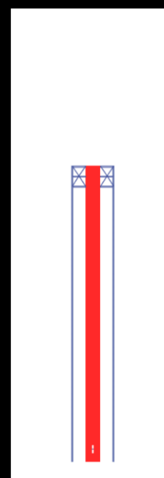
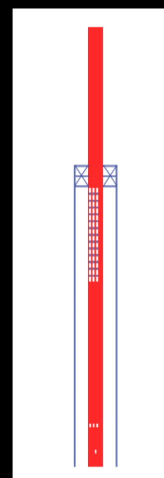
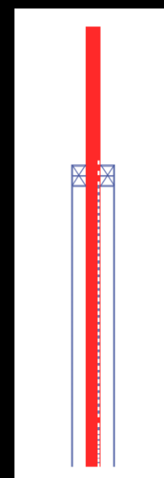


Performance-Based Seismic Design—Why?

- Use of new systems not recognized by ASCE 7
- Buildings with structural height > 240’
  - Exceeds system Height Limit per ASCE 7
- Steel Buildings with Structural Height > ~160’
  - Excessive code-prescriptive column axial demands per AISC 341

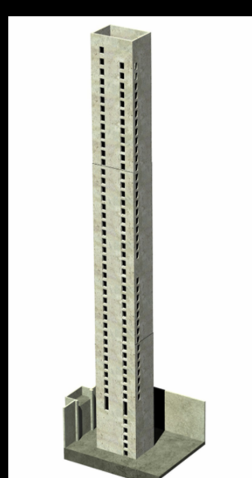
Performance-Based Seismic Design—Why?

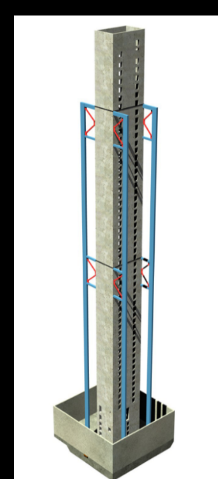



17

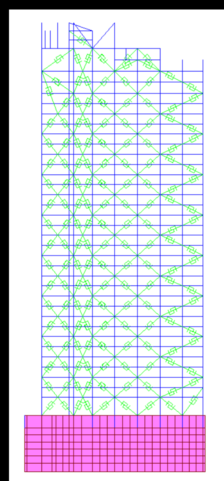
Performance-Based Seismic Design—Why?

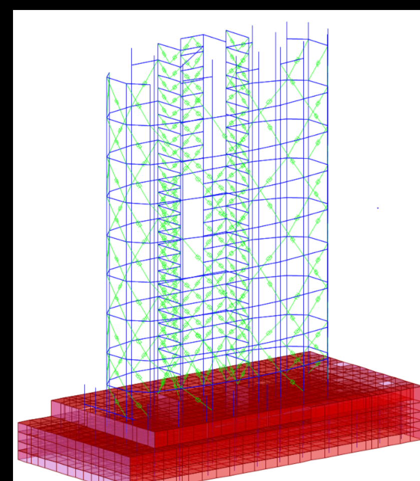





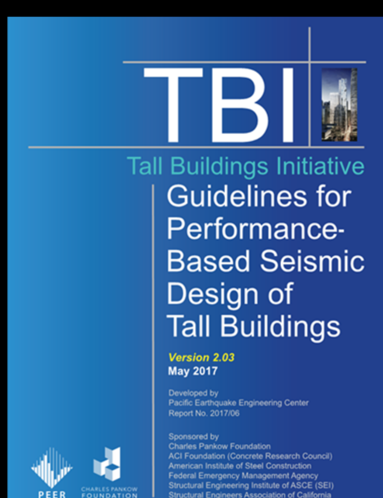
18

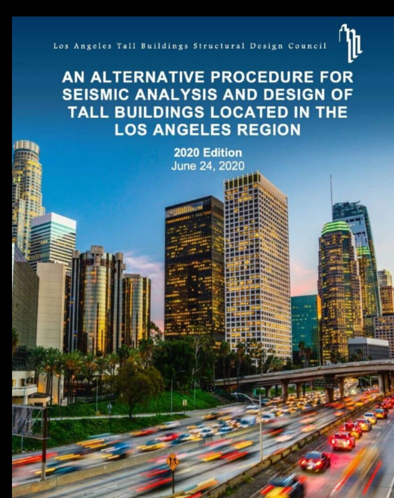
Performance-Based Seismic Design—Why?



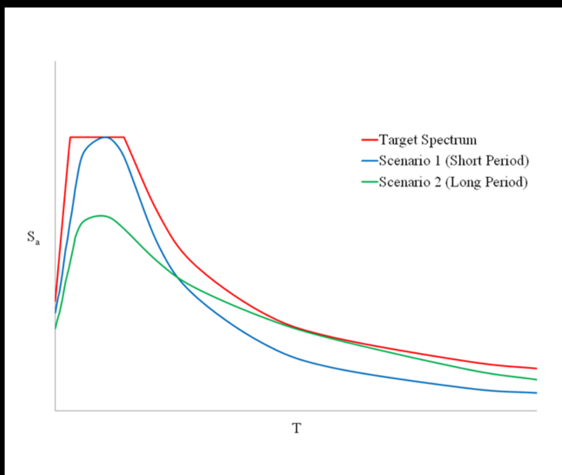


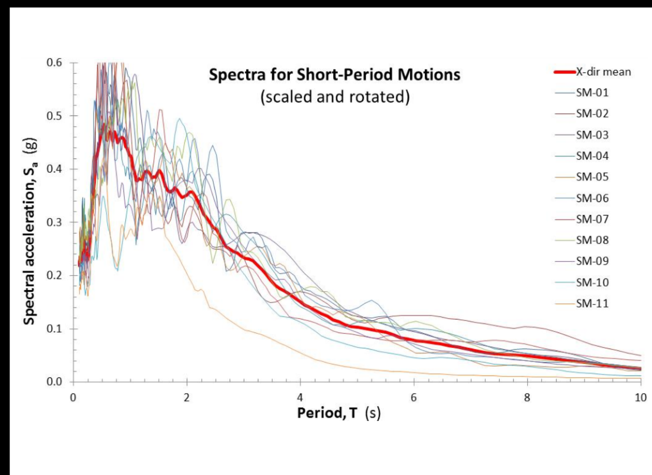
Performance-Based Seismic Design—How?





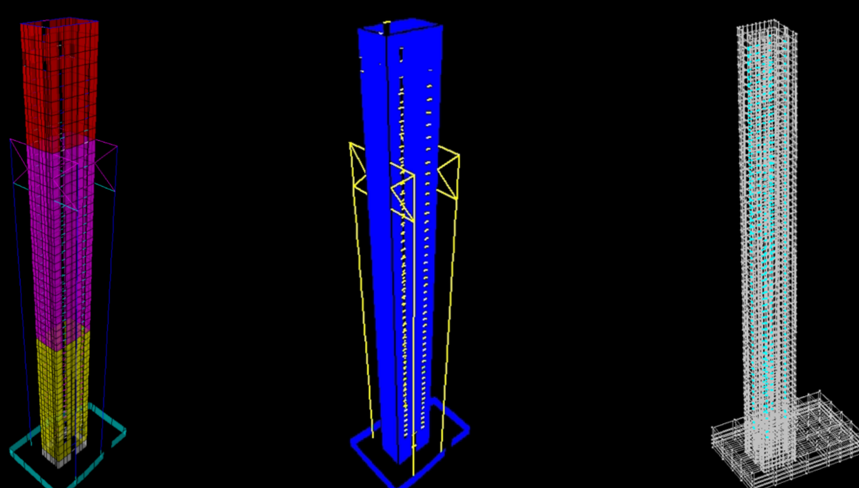
Performance-Based Seismic Design—How?





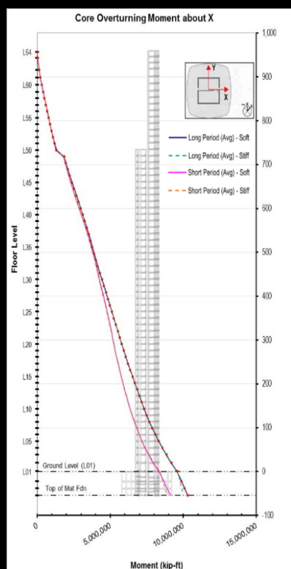
21

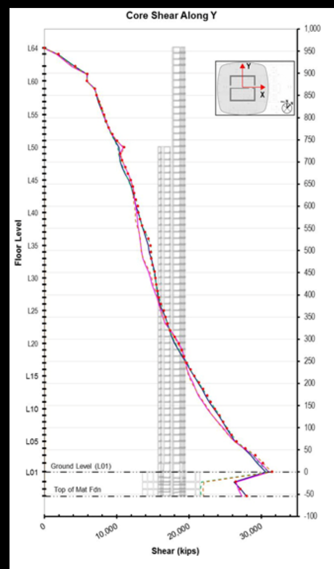
Performance-Based Seismic Design—How?

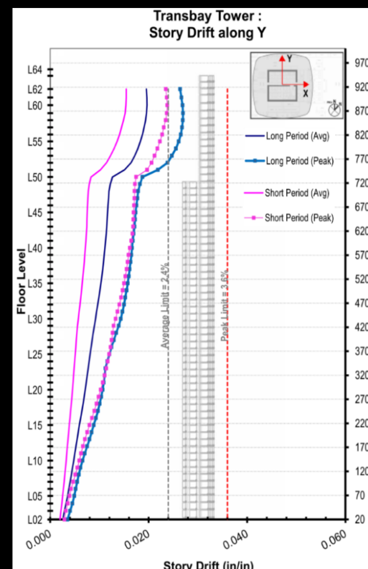


22

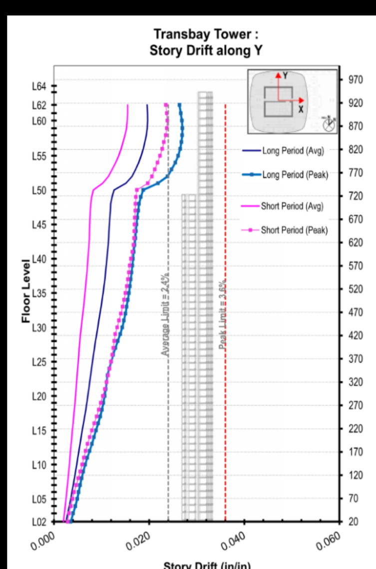
Performance-Based Seismic Design—How?

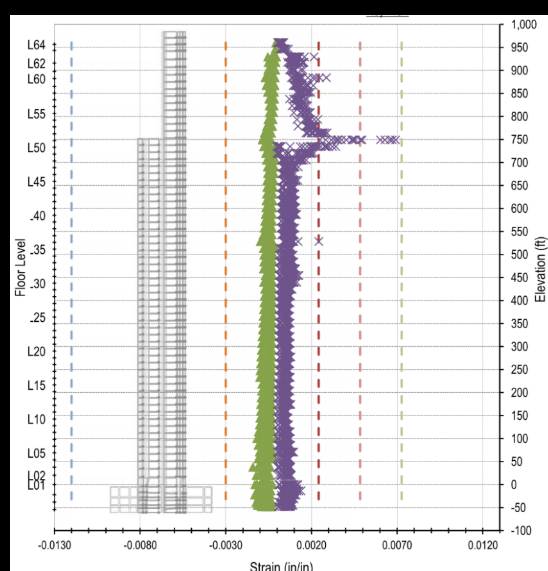






Performance-Based Seismic Design—How?





Performance-Based Seismic Design—How?

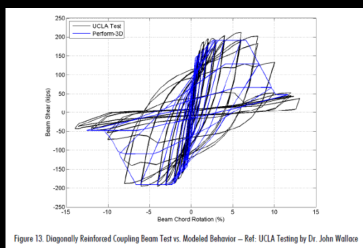


Figure 13: Diagonally Reinforced Coupling Beam Test vs. Modeled Behavior – Ref: UCLA Testing by Dr. John Wallace

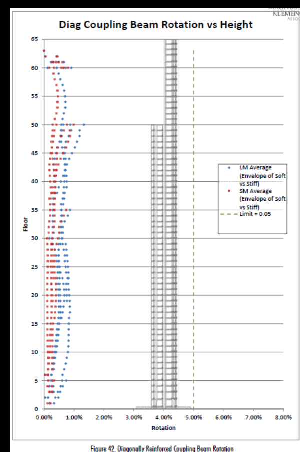


Figure 42. Diagonally Reinforced Coupling Beam Rotation

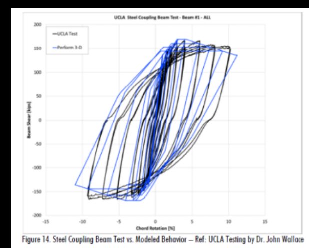


Figure 14. Steel Coupling Beam Test vs. Modeled Behavior – Ref: UCLA Testing by Dr. John Wallace

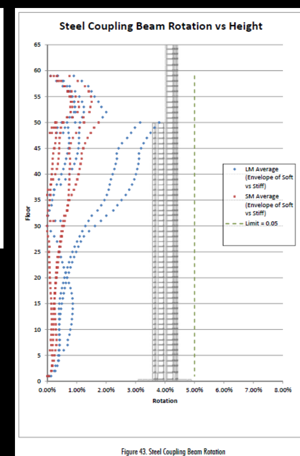
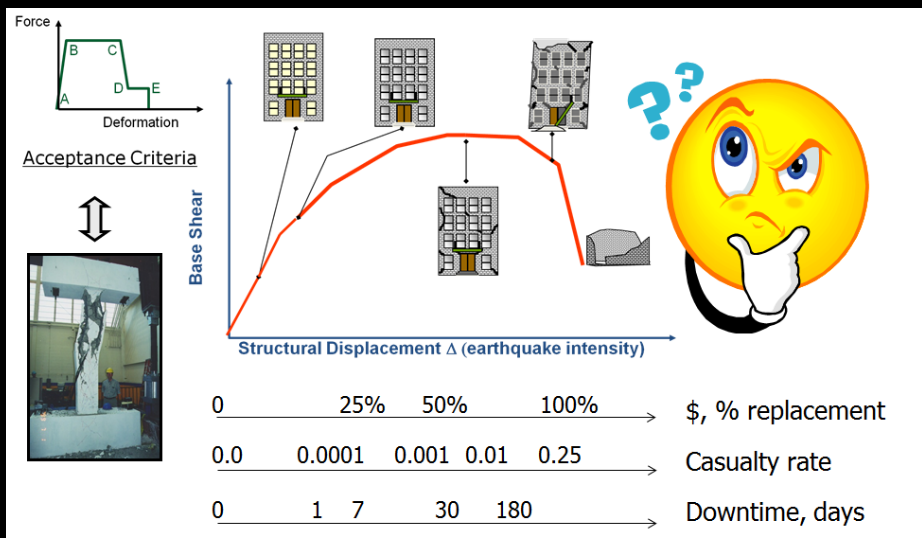


Figure 43. Steel Coupling Beam Rotation

Performance-Based Seismic Design—How?

Performance-Based Seismic Design—The Future



27

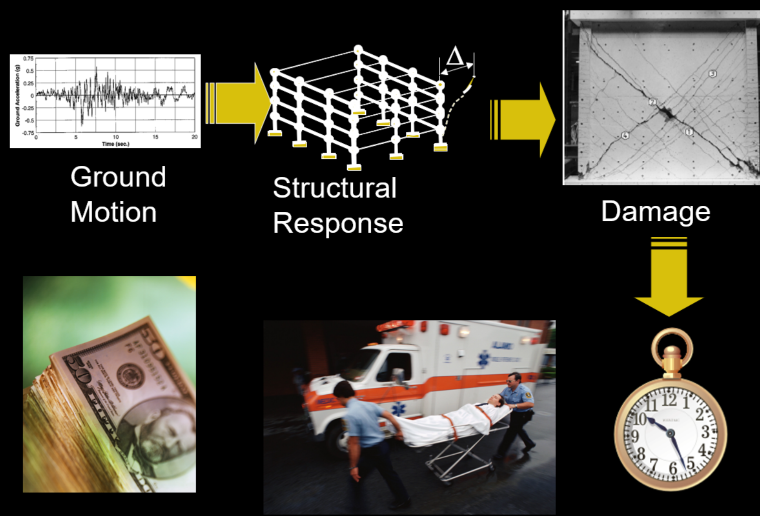
Performance-Based Seismic Design—The Future

FEMA P-58
Methodology

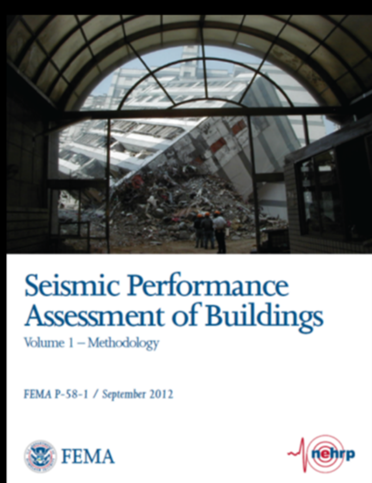
28

Performance-Based Seismic Design—The Future

FEMA P-58 Methodology

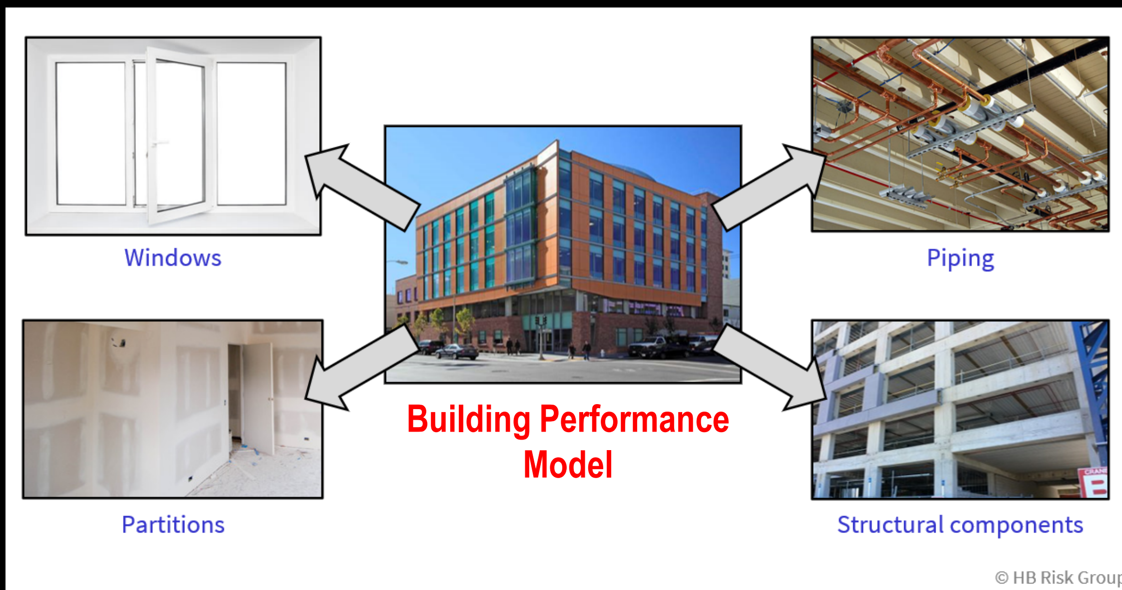


FEMA P-58 Methodology



- First Released September 2012
- Procedure to quantify building seismic performance by probability of:
  - Casualties
  - Repair Costs
  - Repair Time
  - Unsafe Placards
  - Environmental Impacts (2015)

FEMA P-58 Methodology

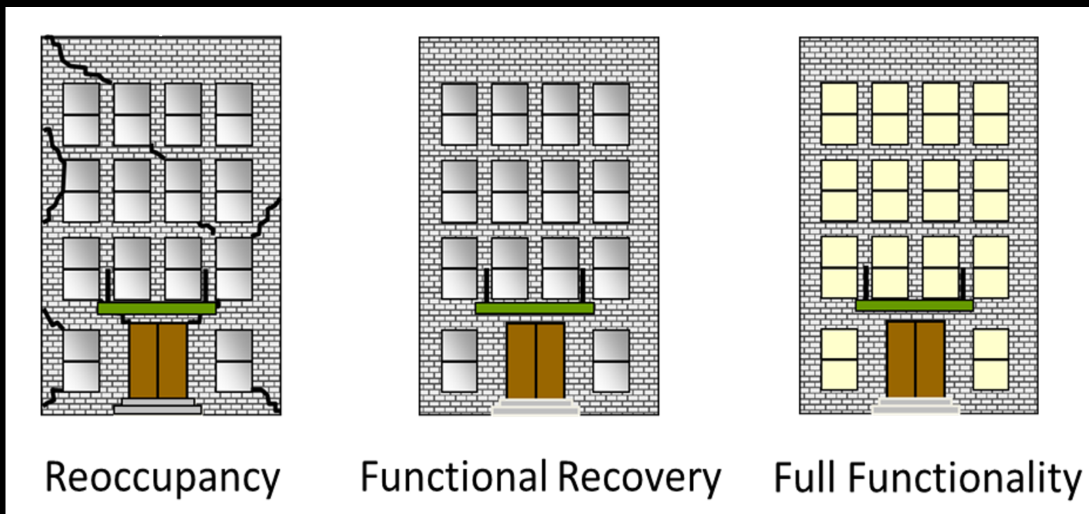


Performance-Based Seismic Design—The Future

Table 6-1 Generalized Performance Expectations for Code-Conforming Buildings

Performance Measure	Performance Expectation	
	Design EQ	MCE
Risk Category II — Office		
Repair Cost	10%	30%
Repair Time	45 Days	150 Days
Casualty Rate	1.0%	2.0%
Probability of Unsafe Placard	20%	40%
Repairability	95%	80%

Functional Recovery Performance Levels—Functionality



33

Functional Recovery Performance Levels—Functionality

Functional Recovery... is a post-EQ performance state in which a building ...

34

Functional Recovery Performance Levels—Functionality

Functional Recovery... is a post-EQ performance state in which a building ... is maintained, or restored, to ...

35

Functional Recovery Performance Levels

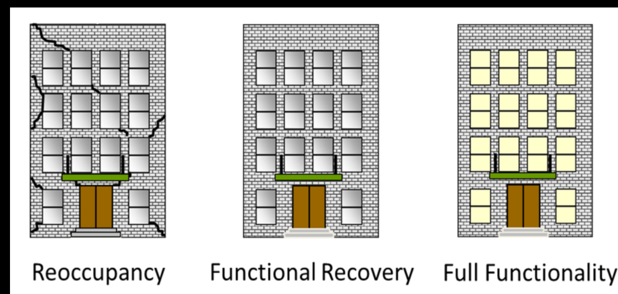
Functional Recovery... is a post-EQ performance state in which a building ... is maintained, or restored, to ... support the basic intended functions associated with the pre-EQ use or occupancy.

36

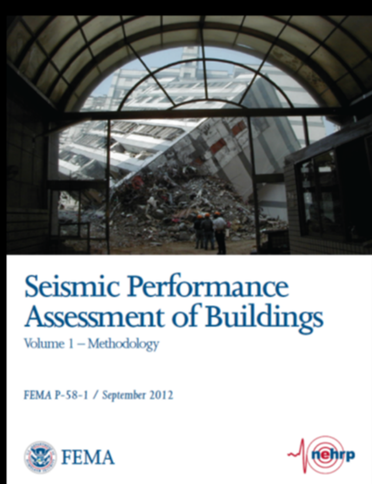
Functional Recovery Performance Levels

To what level of Reliability?

For what level of ground shaking?



FEMA P-58 Methodology—Functional Recovery



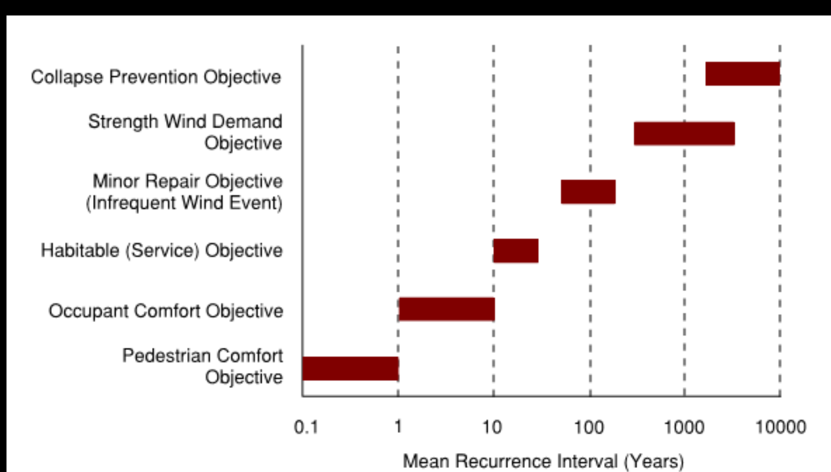
- First Released September 2012
- Procedure to quantify building seismic performance by probability of:
  - Casualties
  - Repair Costs
  - Repair Time
  - Unsafe Placards
  - Environmental Impacts (2015)
  - Functional Recovery Time (2022)

FEMA P-58 Methodology—Functional Recovery

- Assist in
  - Developing Functional Recovery Framework
  - Establishing Functional Recovery Objectives
  - Establishing Design Criteria, including Seismic Hazard
- Resulting in
  - Model Code Provisions
  - Technical Standards
  - Interim Community Provisions

Performance-Based Wind Design – Why?

- To assess the full spectrum of relevant wind performance criteria



Performance-Based Wind Design – Why?

- Improve seismic performance where the Seismic Force-Resisting System ductility is hampered by wind demands
  - Ductile seismic elements may have to be strengthened for elastic wind loads
  - If so, their ability to initiate yield is reduced
  - And force-controlled components see higher demands

41

Performance-Based Wind Design – How?

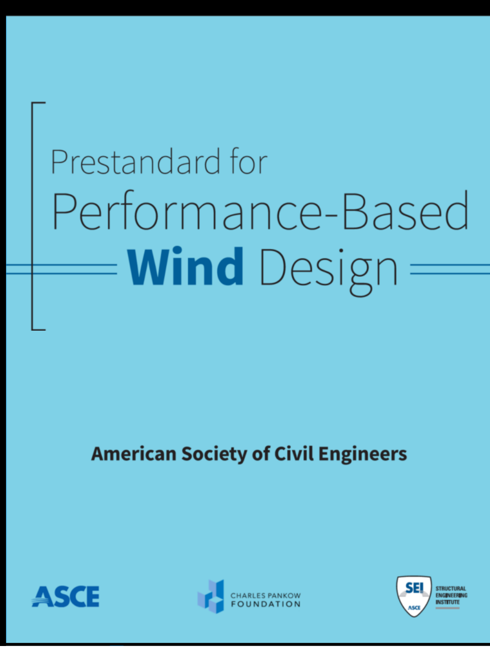
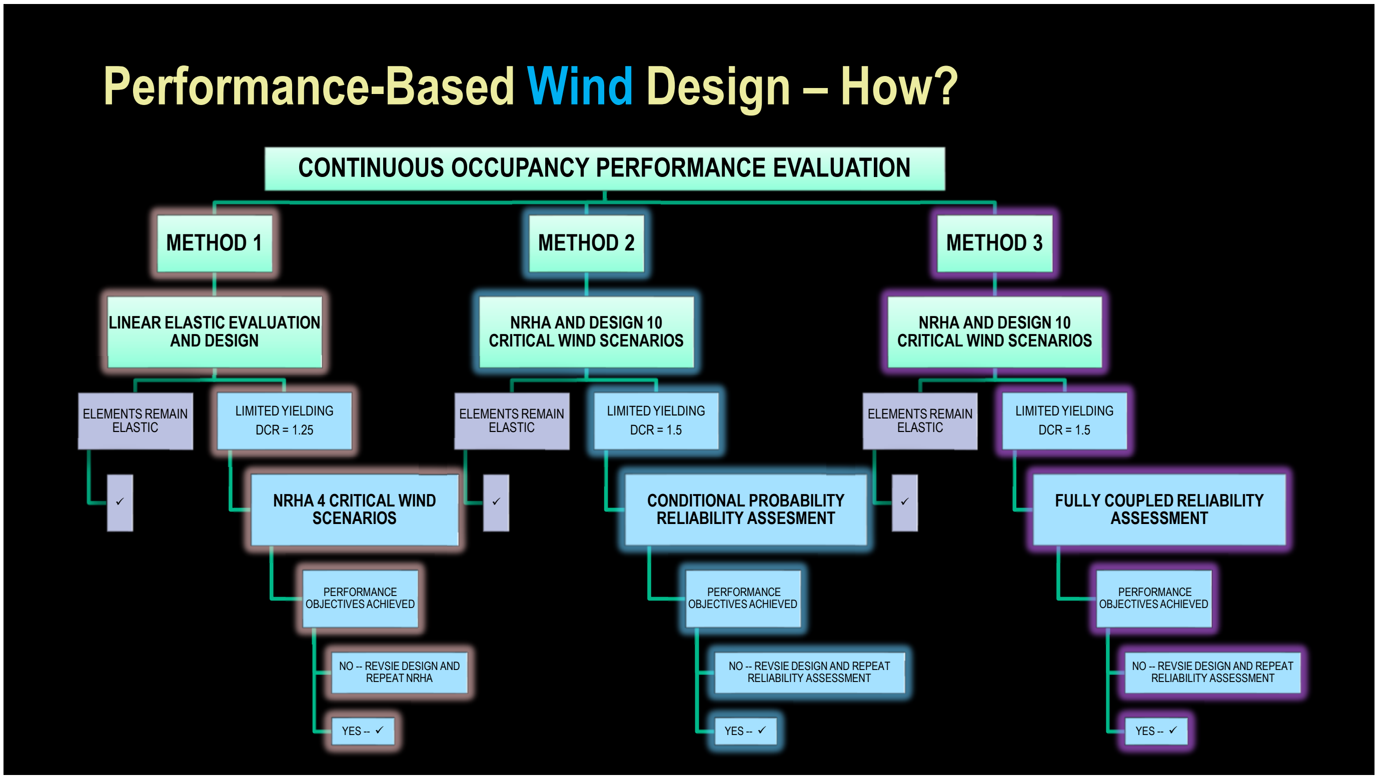


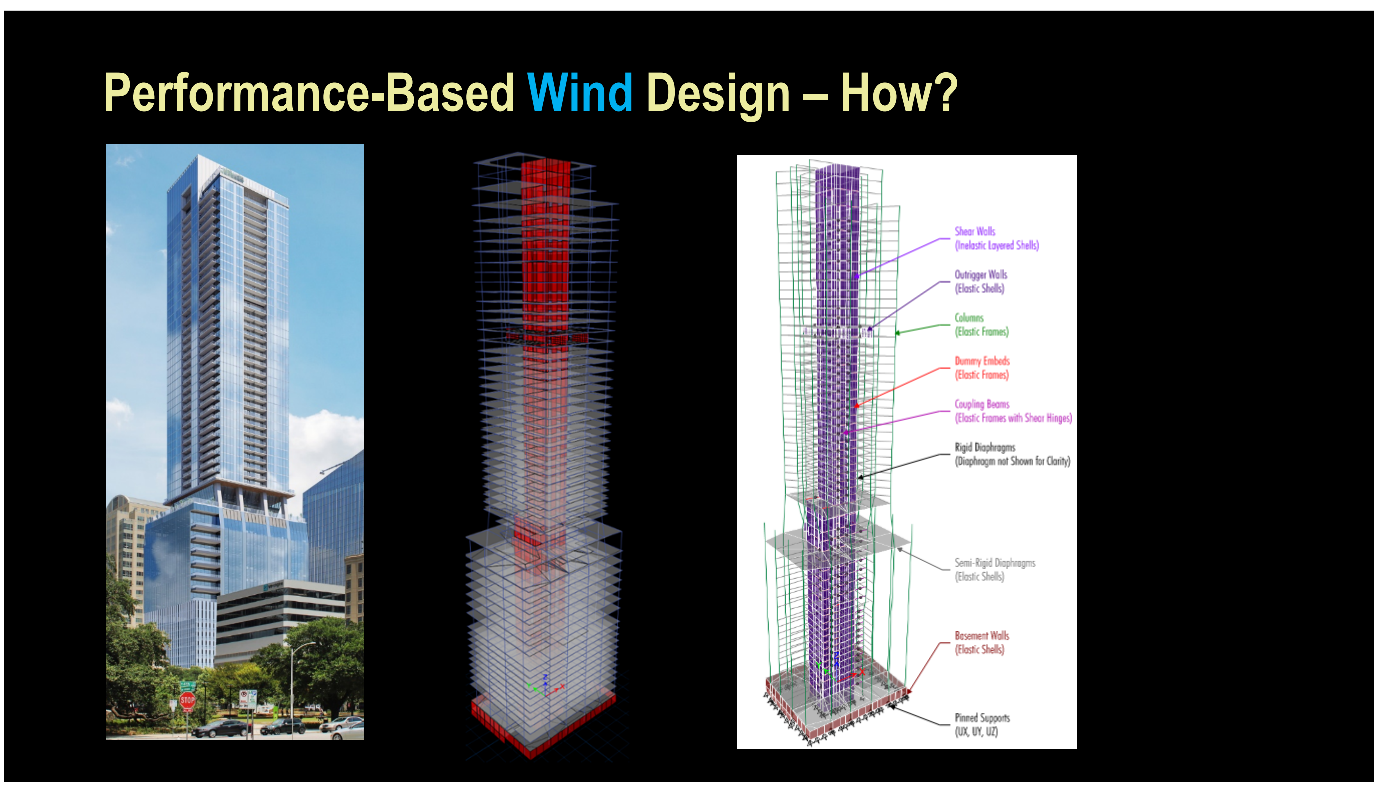
Table 4-1. Performance Objectives and Acceptance Criteria.

	Occupant Comfort	Operational	Continuous Occupancy, Limited Interruption
Risk Category II	Risk category independent	10-years MRI	700-years MRI
Risk Category III		25-years MRI	1,700-years MRI
Risk Category IV		50-years MRI	3,000-years MRI
MWFRS	Performance Objective: The structural system shall remain elastic. The building motions and vibrations shall minimize occupant discomfort at design wind 1-month, 1-year, and 10-years MRI. Acceptance Criteria: See Section 7.2	Performance Objective: The structural system shall remain elastic. The building systems shall remain operational during the wind event for the building risk category. Acceptance Criteria: See Section 7.3	Performance Objective: Specific elements or components of the structural system shall be permitted to become inelastic. The structural system shall withstand a design wind event for the building risk category with a low probability of partial or total collapse. Acceptance Criteria: See Section 7.4
Building Envelope		Performance Objective: The building envelope shall remain attached to the structure. The building envelope shall maintain wind-driven rain resistance. Acceptance Criteria: See Section 8.3	Performance Objective: The building envelope shall remain attached to the structure. The building envelope system shall be designed to maintain wind-driven rain resistance for 25-year MRI wind events for Risk Category II and 50-year MRI wind events for Risk Category III and IV. Acceptance Criteria: See Section 8.3
Nonstructural Components and Systems		Performance Objective: Nonstructural components and systems shall remain attached and maintain wind-driven rain resistance. Acceptance Criteria: See Sections 7.3.1 and 8.4.3	Performance Objective: Nonstructural components and systems shall remain attached. Acceptance Criteria: See Sections 7.4.1 and 8.4.3

42


Performance-Based Wind Design – How?
CONTINUOUS OCCUPANCY PERFORMANCE EVALUATION
METHOD 1
LINEAR ELASTIC EVALUATION AND DESIGN
ELEMENTS REMAIN ELASTIC
✓
LIMITED YIELDING DCR = 1.25
NRHA 4 CRITICAL WIND SCENARIOS
PERFORMANCE OBJECTIVES ACHIEVED
NO – REVSIE DESIGN AND REPEAT NRHA
YES – ✓
METHOD 2
NRHA AND DESIGN 10 CRITICAL WIND SCENARIOS
ELEMENTS REMAIN ELASTIC
✓
LIMITED YIELDING DCR = 1.5
CONDITIONAL PROBABILITY RELIABILITY ASSESMENT
PERFORMANCE OBJECTIVES ACHIEVED
NO – REVSIE DESIGN AND REPEAT RELIABILITY ASSESSMENT
YES – ✓
METHOD 3
NRHA AND DESIGN 10 CRITICAL WIND SCENARIOS
ELEMENTS REMAIN ELASTIC
✓
LIMITED YIELDING DCR = 1.5
FULLY COUPLED RELIABILITY ASSESSMENT
PERFORMANCE OBJECTIVES ACHIEVED
NO – REVSIE DESIGN AND REPEAT RELIABILITY ASSESSMENT
YES – ✓

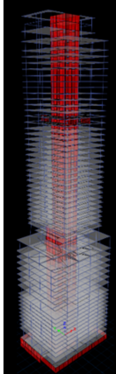
43

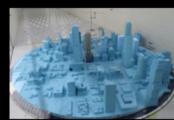

Performance-Based Wind Design – How?
Shear Walls
(Inelastic Layered Shells)
Outrigger Walls
(Elastic Shells)
Columns
(Elastic Frames)
Dummy Embeds
(Elastic Frames)
Coupling Beams
(Elastic Frames with Shear Hinges)
Rigid Diaphragms
(Diaphragm not Shown for Clarity)
Semi-Rigid Diaphragms
(Elastic Shells)
Basement Walls
(Elastic Shells)
Pinned Supports
(UX, UY, UZ)

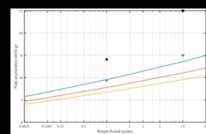
44

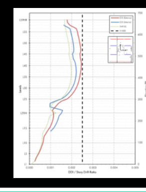
Performance-Based Wind Design – How?

Method 1





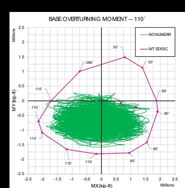


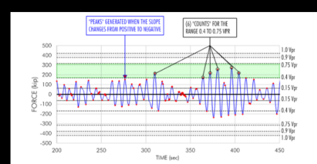


(1) INITIAL PROPORTIONING LATERAL SYSTEM → (2) CONDUCT WIND TUNNEL TESTING → (3) ASSESS OCCUPANT COMFORT - ACCELERATIONS → (4) ASSESS OPERATIONAL PERFORMANCE - DRIFT → (5) DESIGN FOR LRHA

- PERMIT LIMITED YIELDING IN DEFORMATION-CONTROLLED ELEMENTS
- ASSESS FORCE-CONTROLLED ELEMENT STRESSES

→ (6) BUILD ENHANCED NRHA MODEL → (7) CONDUCT NRHA → (8) ASSESS GLOBAL PERFORMANCE AND ACCEPTANCE CRITERIA → (9) REDESIGN AND REPEAT NRHA IF NECESSARY





Questions???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