SEAOSC Webinar

Performance-Based Design and Resilience-Based Design of Steel and Concrete Moment Frame Buildings

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Co-Founder and CEO @ Seismic Performance Prediction Program (SP3)

www.hbrisk.com

Presentation Overview

- Overview of design methods (code, PBEE, RBEE)
- Performance-Based and Resilience-Based Design
  - ✓ Design objective
  - ✓ Governing codes and guidelines
  - ✓ Structural modeling approach
  - ✓ Ground motion selection and scaling
  - ✓ Acceptance criteria
  - ✓ Recent project examples
- Recent and ongoing research to better enable Resilience-Based Design
- Summary and closing

Design Method Options

Code Design (ASCE7, etc.)

- Safety Goal – Yes
- Accept damage, repair cost/time, and possible demolition (R >> 1)

"Performance-Based Design" (LATBSDC, AB 083, ASCE 41, etc.)

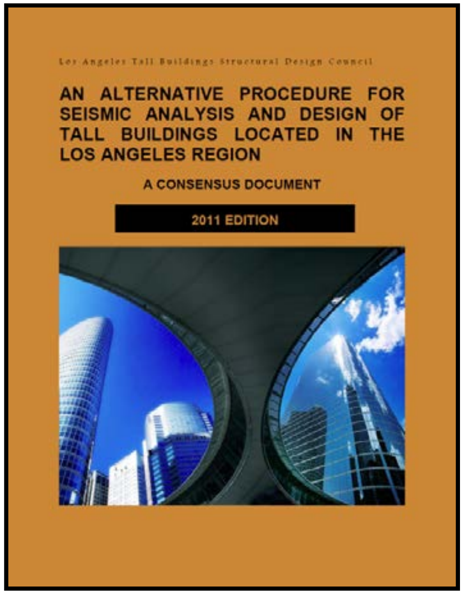
- Safety Goal – Yes
- Typically accept damage, repair cost/time, and possible demolition (R >> 1)
- Can consider other goals, but typically not done in current practice
- Enhanced modeling and design scrutiny

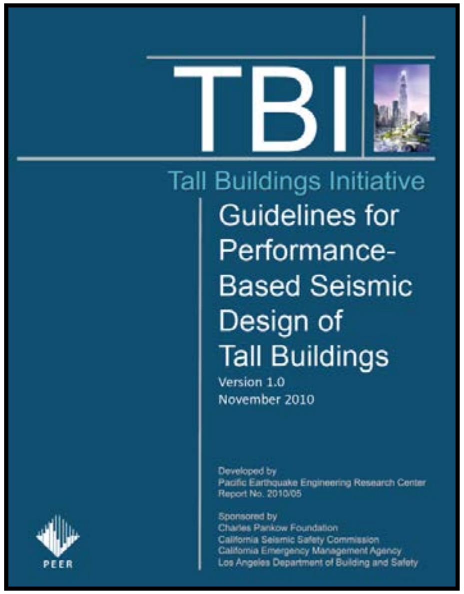
"Resilience-Based Design" (or "PBD Generation 2")

- Safety Goal – Yes
- Repair Time Goal – Yes
- Repair Cost Goal – Yes
- Also can have enhanced modeling and design scrutiny

Performance-Based Earthquake Engineering

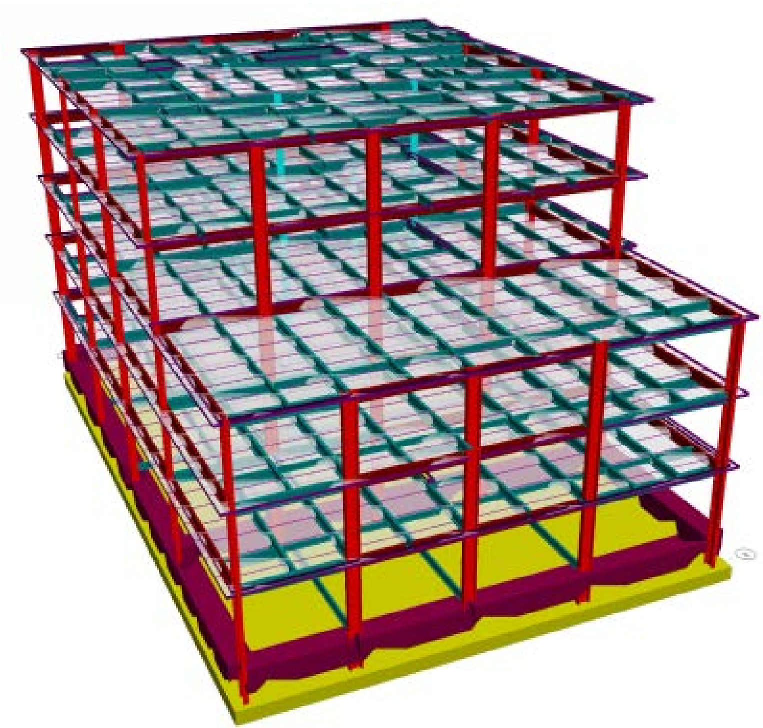
- PBEE has been around for some time now (not new).
- Design objectives:
  - ✓ PBEE framework can handle safety, IO, etc.
  - ✓ However, typically used as an “alternate means” approach to show equivalent safety/performance to code design.
- Codes and Guidelines:





PBEE: Structural Modeling

- Structural modeling approach:
  - ✓ Nonlinear modeling
  - ✓ Typically response-history analysis (which requires selection and scaling of ground motions)
- Common technologies:
  - ✓ Elastic: RAM, Etabs, etc.
  - ✓ Nonlinear: CSI Perform3D typical
- Guidelines for nonlinear modeling:
  - ✓ Some past publications (e.g. ATC-72), but detailed guidance lacking for nonlinear dynamic.
  - ✓ NIST commissioned the ATC-114 project to enhance guidance.



[Image: Steve Bono, SGH, ATC-114 project]

PBEE: Structural Modeling (ATC-114)

- ATC-114 report to be released shortly (in final editing process now)
- Upcoming SEAONC Webinar on May 31st and upcoming ATC webinar with more details

PBEE: Structural Modeling (ATC-114)

Part I: General Guidelines

Part IIa: Guidelines Specific to Steel Moment Frames

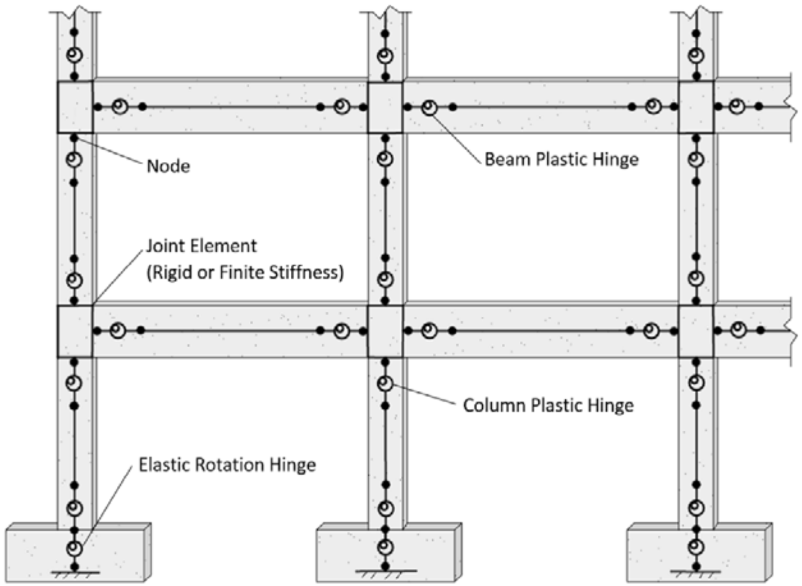
Part IIb: Guidelines Specific to RC Moment Frames

Part IIc: Guidelines Specific to RC Shear Walls

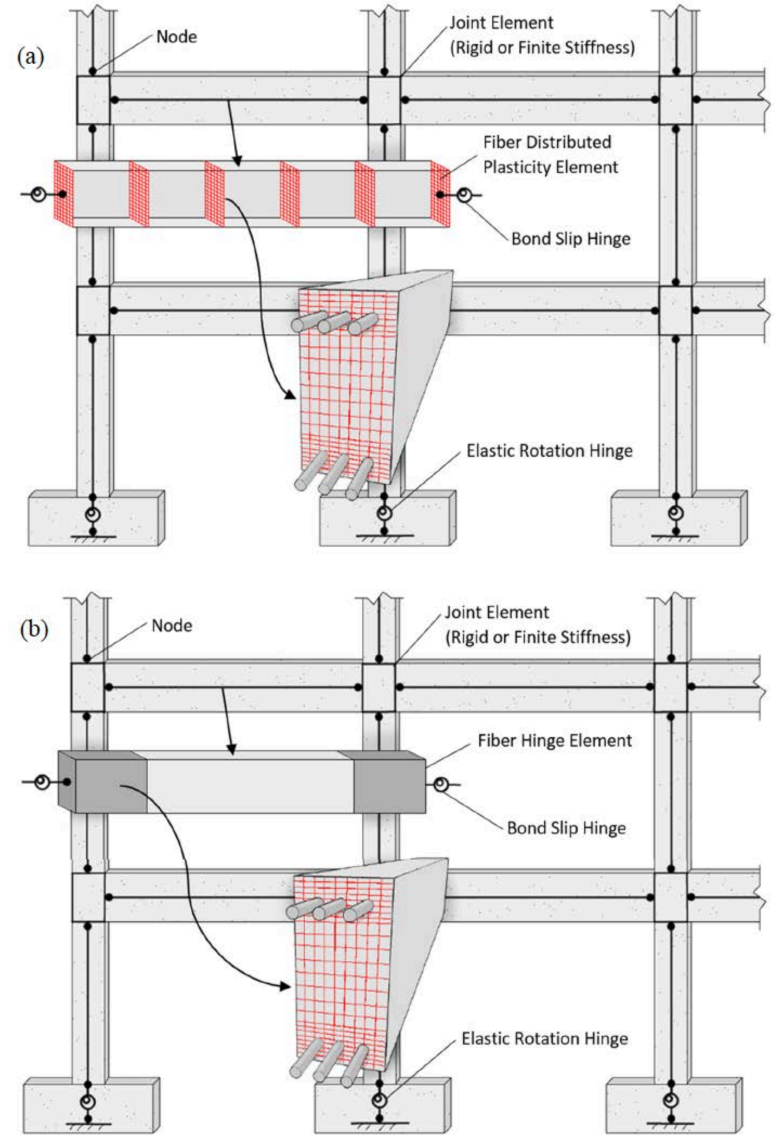
Part IId: Guidelines Specific to Steel Braced Frames

…

PBEE: Structural Modeling (ATC-114)

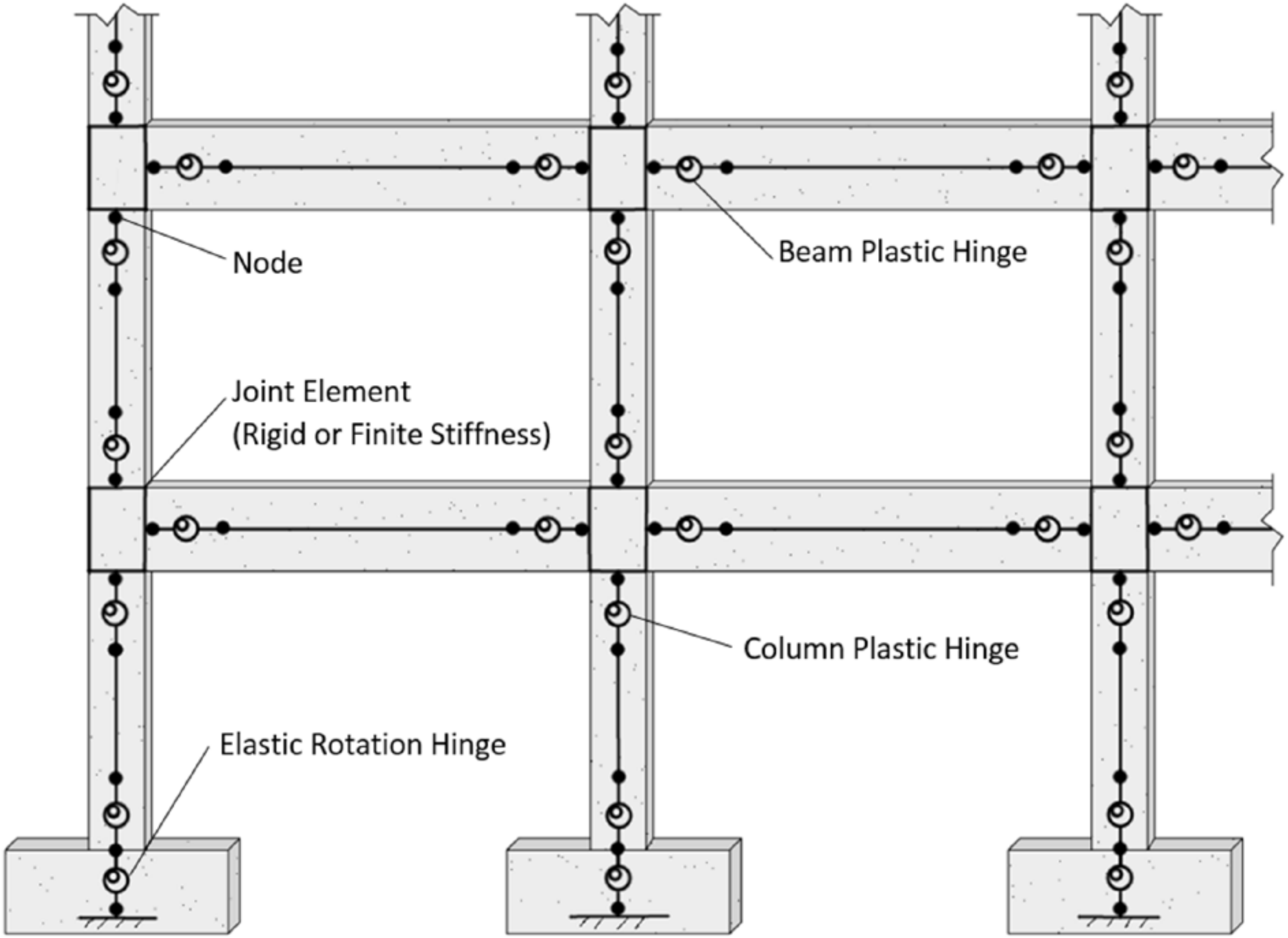


Concentrated Hinge

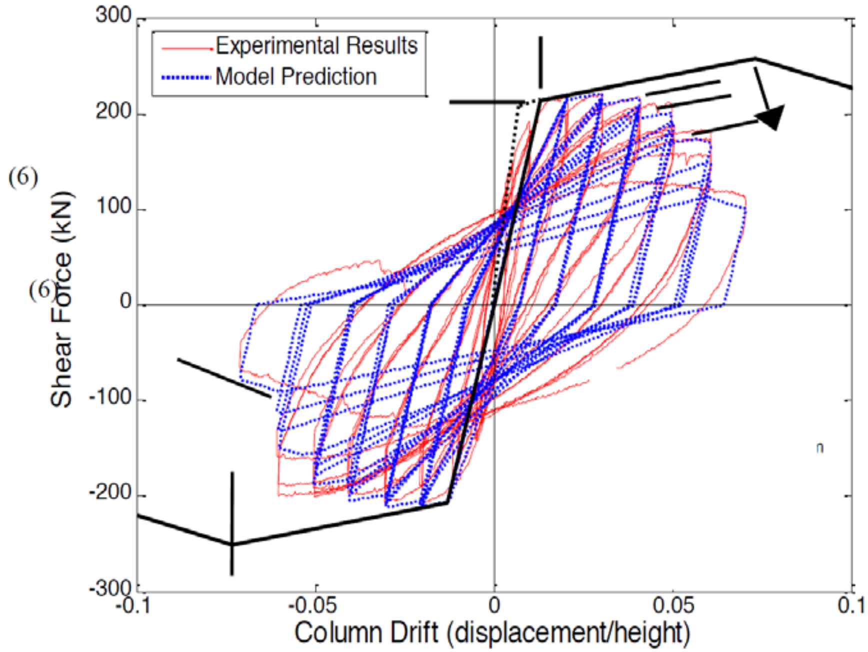


Fiber-Type Elements

PBEE: Structural Modeling (ATC-114)



PBEE: Structural Modeling (ATC-114)



Key Response Parameters:

- strength
- initial stiffness
- post-yield stiffness
- plastic rotation (capping) capacity
- post-capping slope
- cyclic deterioration rate

Calibration Process:

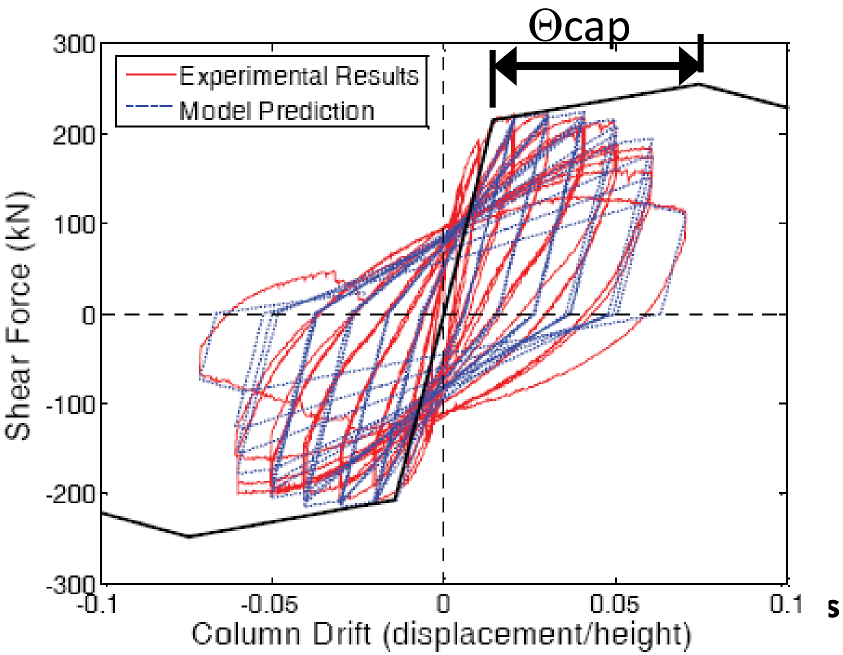
- 250+ columns (PEER database)
- flexure & flexure-shear dominant
- calibrated to *expected* values

PBEE: Structural Modeling (ATC-114)

$$\theta_p = 0.12(1+0.55a_{sl})(0.16)^{\nu}(0.02+40\rho_{sh})^{0.43}(0.54)^{0.01c_{units}f_c'}(0.66)^{0.1s_n}(2.27)^{10.0\rho}$$

Key Design/Detailing Variables:

ρ_{sh} – amount of steel stirrups
ν – axial load ratio (*P/Ag f'c*)
s_n – tie spacing
a_{sl} – joint bond slip

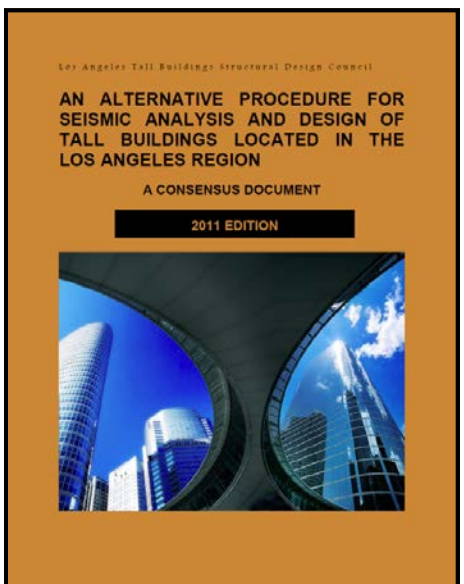


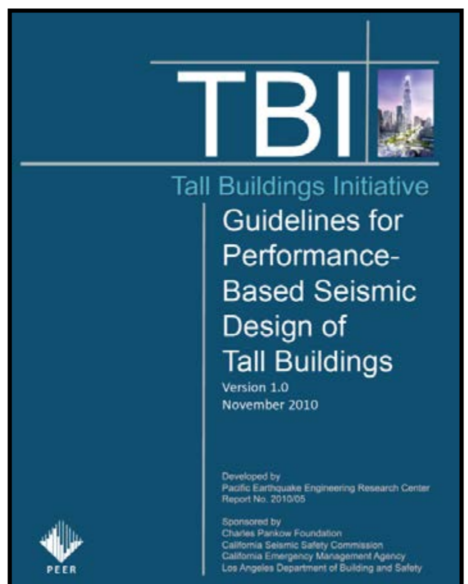
Dispersion:

$\sigma_{ln} = 0.54$

PBEE: Acceptance Criteria

- So far, we have talked about doing a lot of detailed nonlinear modeling.
- **Structural responses** do not tell us about performance until to compare with the **acceptance criteria**.
- The acceptance criteria will depend on what document is being used to govern the design.





PBEE: Acceptance Criteria (ASCE 7-16 Chp. 16)

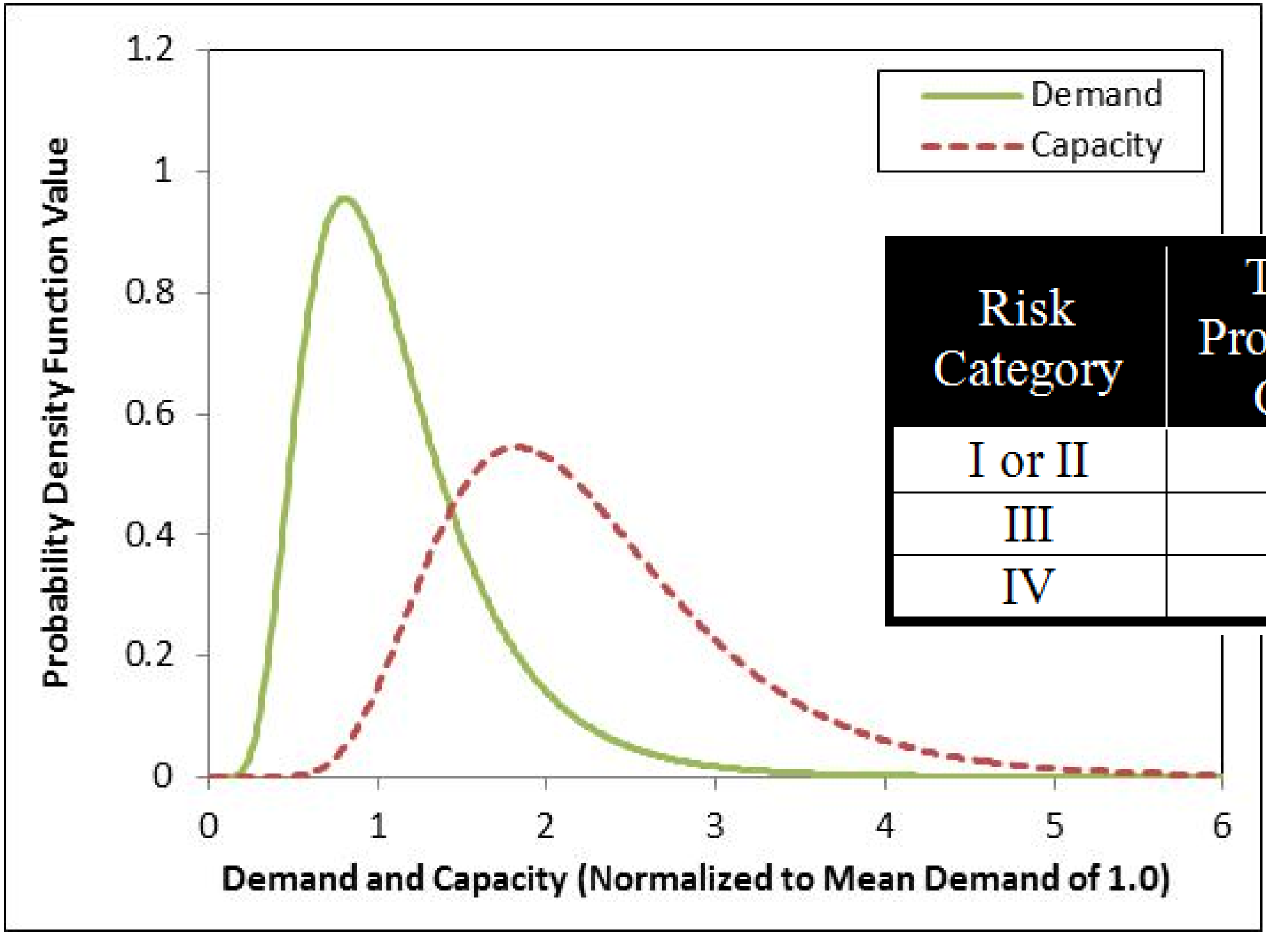
- **Big Focus of ASCE 7-16 Chapter 16 Revision:** Develop acceptance criteria more clearly tied to the ASCE7 safety goals.

Risk Category	Tolerable Probability of Collapse	Ground Motion Level
I or II	10%	MCE_R
III	6%	MCE_R
IV	3%	MCE_R

- **Explicit Goal:** Acceptable collapse probability.
- **Implicit Verification Approach:** Use average structural responses (with 11 motions) to show compliance.

PBEE: Acceptance Criteria (ASCE 7-16 Chp. 16)

- Force-controlled (brittle) components:



Risk Category	Tolerable Probability of Collapse	Ground Motion Level
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PBEE: Acceptance Criteria (ASCE 7-16 Chp. 16)

- Force-controlled (brittle) components:

$2.0\, I_e\, F_u \leq F_e$ for "critical" (same as PEER-TBI)

$1.5\, I_e\, F_u \leq F_e$ for "ordinary"

$1.0\, I_e\, F_u \leq F_e$ for "non-critical"

F_u = mean demand (from 11 mo

F_e = expected strength

Contrast: Much more stringent that the average-based approach that could be used in ASCE 41.

Critical = failure causes immediate global collapse
Ordinary = failure causes local collapse (one bay)
Non-critical = failure does not cause collapse

PBEE: Acceptance Criteria (ASCE 7-16 Chp. 16)

- ASCE 7-16 Chapter 16 also has acceptance criteria for:
  - ✓ Ductile deformation-controlled components (e.g. hinge rotations)
  - ✓ Interstory drifts (average)
  - ✓ Limits on collapses or non-converged cases
  - ✓ Strength of initial design step (using an ASCE 7 elastic design approach)

PBEE: Current Projects

- Being used on many tall buildings on the U.S. west coast and beyond
- Primarily (or solely) used for code equivalence (safety check)

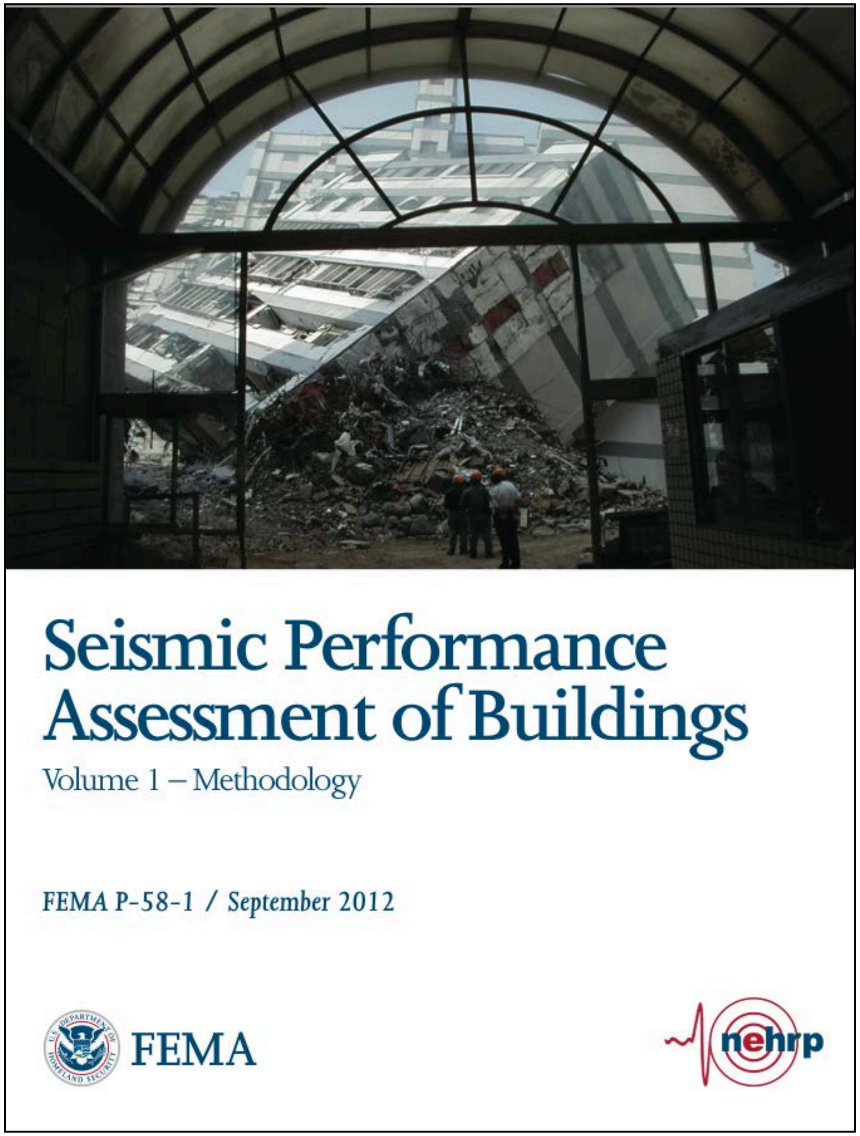
[Image: SF Gate, Skidmore, Owings & Merrill, LLP]

Resilience-Based Earthquake Engineering

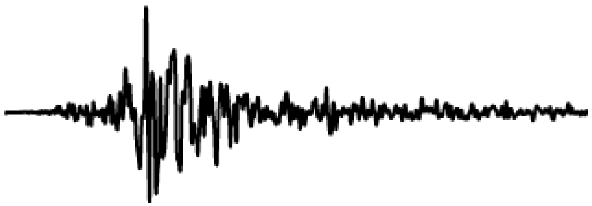
- The *concept* of designing for resilience is not new.
- Resilient design has it's roots in PBEE.
- However, PBEE typical focuses on safety (code equivalence).
- Also, even if one wanted to look beyond safety (to limit damage, repair cost, and repair time), there have not been supporting analysis methods until recently.
- "Resilience-based" earthquake engineering (or PBEE Generation 2), looks at:
  - ✓ Ensuring safety (either directly, or through code-compliance)
  - ✓ Limiting repair costs
  - ✓ Limiting repair and building closure time
- Codes and Guidelines: FEMA P-58 (released in 2012)

RBEE: Codes and Guidelines (FEMA P-58)

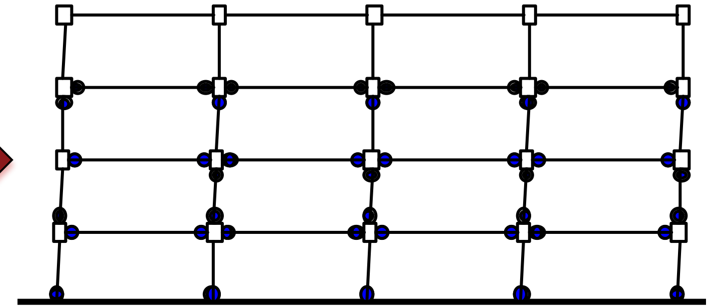
- FEMA P-58 is a probabilistic performance assessment method (10+ years in the making, $12M+ invested, development ongoing)
- FEMA P-58 is tailored for building-specific analysis (in contrast to most resiliency/risk assessment methods)
- FEMA P-58 output results:
    1) Repair costs
    2) Repair time
    3) Safety: Fatalities & injuries



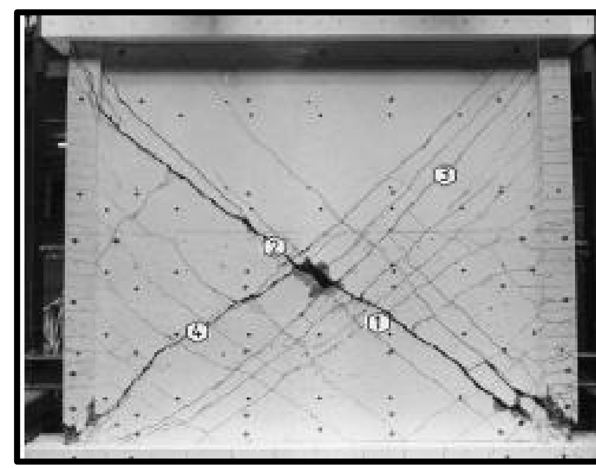
RBEE: Codes and Guidelines (FEMA P-58)



Ground Motion Hazard



Structural Response



Component Damage

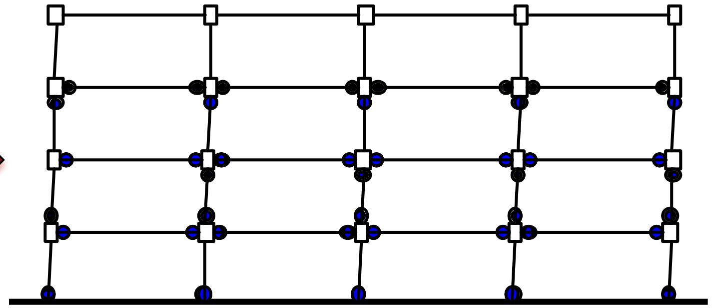
Casualties

Repair Time

Economic Loss

RBEE: Structural Modeling

Ground Motion Hazard



Structural Response

- Structural modeling step
  - Story drift ratio at each story
  - Peak floor acceleration at each floor

Option #1: Response-history structural analysis
[it is a ***misconception*** that this is required for resilient design]

Option #2:

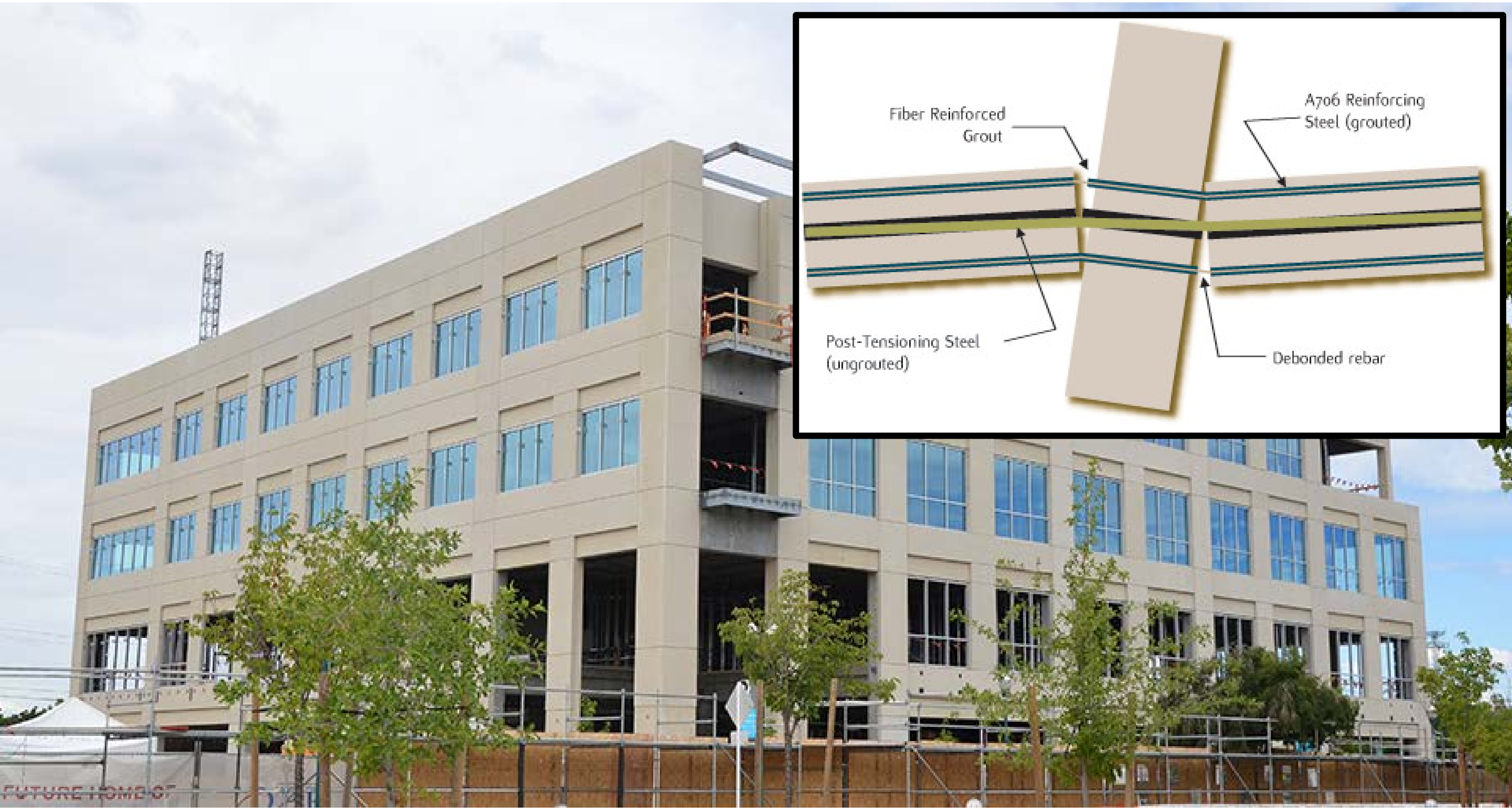
- FEMA P-58 Simplified Method (period, strength, mode shape)
- SP3 Structural Response Prediction Engine (three modes, strength, etc.)

RBEE: Acceptance Criteria

- Resiliency acceptance criteria depends on document used and the desired level of resiliency.

Level of Resilience	Maximum Damage (% value)	Maximum Recovery Time	Safety
Platinum	5%	5 days	Safe
Gold	10%	4 weeks	Safe
Silver	20%	6 months	Safe
Bronze	40%	1 year	Safe

RBEE: Recent Projects



RBEE: Recent Projects

Project Team:

- General Contractor: DPR Construction
- Architect: LPAS
- SEOR: Buehler & Buehler Structural Engineers
- Precaster: Clark Pacific
- Owner: A California Municipality

Resiliency Outcomes:

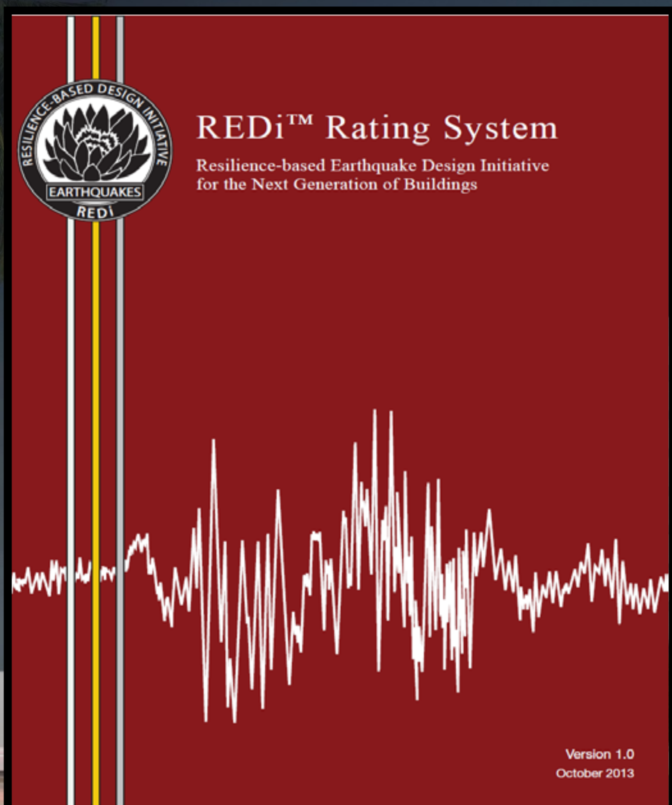
- Safe (few or no injuries)
- Minimal repair cost (>5%)
- Minimal functionality time (>5 days)

USRC: 5 Star Platinum Performance

New Design: Municipal Center (not named)

Figure Source: SOM/NYASE 2016 SEAOC presentation

New Design: Municipal Center (not named)



Project Team

SOM	Structural Engineer of Record M. Sarkisian, E. Long & A. Krebs
NABIH YOUSSEF ASSOCIATES STRUCTURAL ENGINEERS	Structural Engineer of Record N. Youssef, O. Hata & S. Stewart
ARUP	Peer Review Ibbi Almufti
SP3 Haselton Baker Risk Group	Business Continuity Consultant C. Haselton

Figure Source: SOM/NYASE 2016 SEAOC presentation

New Design: Municipal Center (not named)

Design Objectives (for design earthquake):

- Safe (few or no injuries)
- Minimal repair cost (>5%)
- Minimal reoccupancy time (>1 week)
- Minimal functionality time (>1 month)

REDi: ~Gold Performance
USRC: 4-5 Star Performance

Figure Source: SOM/NYASE 2016 SEAOC presentation

RBEE: Recent Projects

Figure Source: SOM/NYASE 2016 SEAOC presentation

- Final Design Outcomes (*relative* comparisons are most compelling):
  - **Repair Cost: ~2%** [5-star] *(Typically 10-20% for new code)*
  - **Recovery Time: Few days** [5-star] *(Typically 6-9mo. for new code)*
  - **Safety:** Low fatality+injury risk and good egress [5-star]

White Paper on Resilient Seismic Design using Prescriptive And Non-Prescriptive Design Methods

C.B. Haselton, PhD, PE
Dustin Cook, PE
Last Updated: March 8, 2017

Introduction and Intended Audience

This short white paper is written for audiences interested in resilient design of new buildings. In this paper, "resilient design" means that the goal is for the building to have limited damage in an earthquake, such that the repair costs and repair time are low. This is in contrast to the typical building-code-based design approach, which focuses primarily on safety (not controlling repair costs and repair time) and often leads to a building that is essentially disposable in a large earthquake.

This paper is also targeted at an audience that is interested in a *quantitative* approach to resilient design rather than an empirical/judgmental approach. This paper is also currently written in language tailored toward a structural engineering audience, but the content is also useful to other audiences such a building code organizations, municipal officials interested in resilient design for their jurisdiction, etc.

RBEE: White Paper on Resilient Design

Requirements for a Resilient Design

There are several levels of resilient design, and the exact design requirements will depend on the level of resilience desired, but the primary needs to make a building be seismically resilient are as follows:

- Essentially no structural damage (i.e. no red tag and no damage that will inhibit building functionality).
- Residual drifts low enough to not cause red tag and not require repair.
- Peak drifts low enough to prevent damage to non-structural drift sensitive components that would inhibit building functionality.
- Peak floor accelerations low enough to prevent damage to acceleration sensitive components (that would inhibit building functionality), or the anchorages and the equipment being specifically designed to remain functional under the imposed floor accelerations.

Table 1 - Example performance targets for building resilience

Level of Resilience	Maximum Damage (% value)	Maximum Recovery Time	Safety
Platinum	5%	5 days	Safe
Gold	10%	4 weeks	Safe
Silver	20%	6 months	Safe
Bronze	40%	1 year	Safe

RBEE: White Paper on Resilient Design

- How do we do resilient design?
- Same approach as any other design!

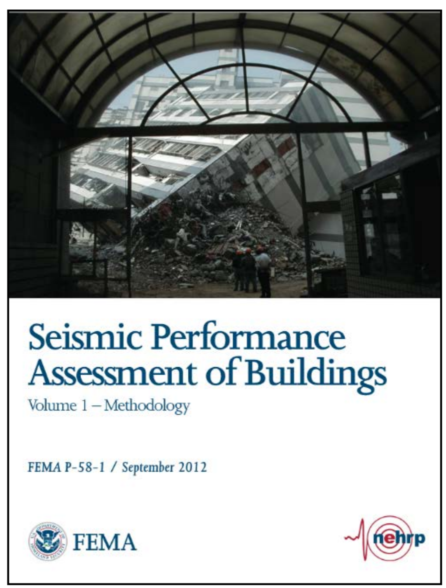


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Table 2 - Example of Resilient Design Process using FEMA P-58

ID	Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
11251	Baseline	17%	43%	37 days

Table 2 - Example of Resilient Design Process using FEMA P-58

ID	Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
11251	Baseline	17%	43%	37 days
11253	Self-Centering Frame (No Residual Drift)	11%	27%	32 days
11254	Cladding Detailed for No Damage	7%	17%	29 days
11255	Slab-Column Connections Detailed for No Damage	4%	11%	27 days
11256	Lateral Frame Connections Detailed for No Damage	2%	5%	27 days
11257	Elevators Detailed for No Damage	2%	5%	4 days

Table 2 - Example of Resilient Design Process using FEMA P-58

ID	Design Changes	Mean Loss at 10% in 50yr	Mean Loss at 2% in 50yr	Median REDi Functional Recovery at 10% in 50yr
11251	Baseline	17%	43%	37 days
11253				ays
11254				ays
11255				ays
11256				ays
11257				ys

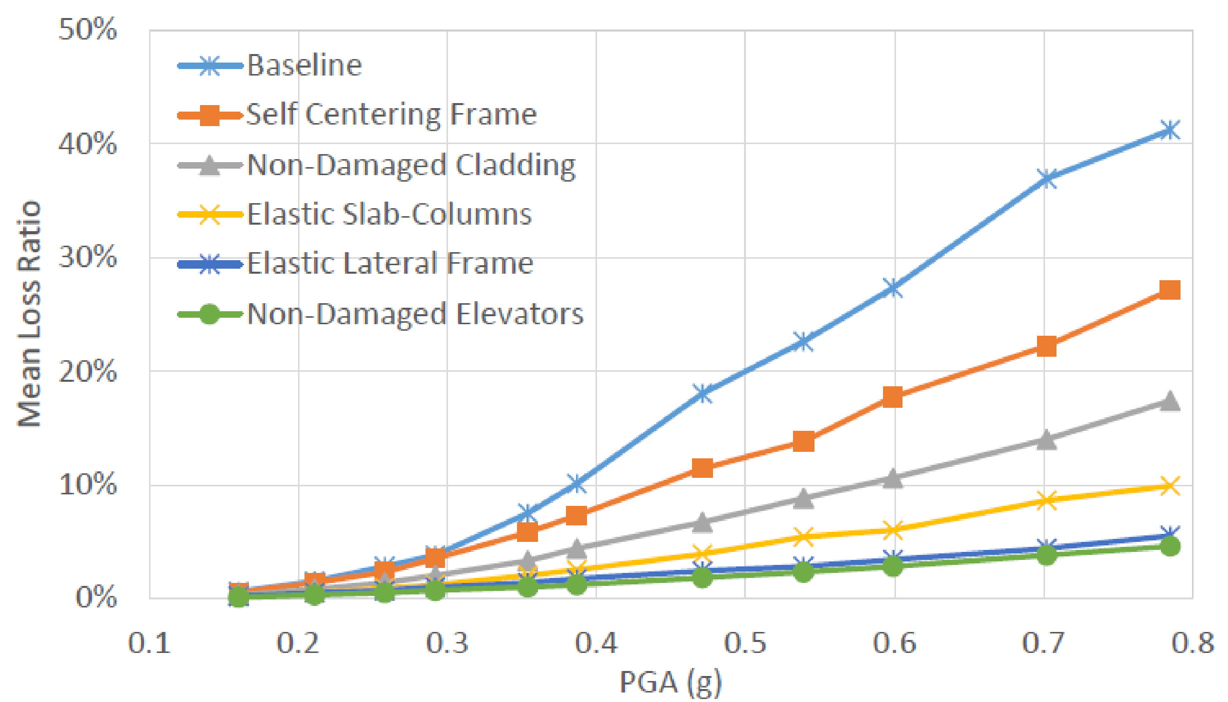


Figure 1 - Example Results from a Resilient Design Process using FEMA P-58

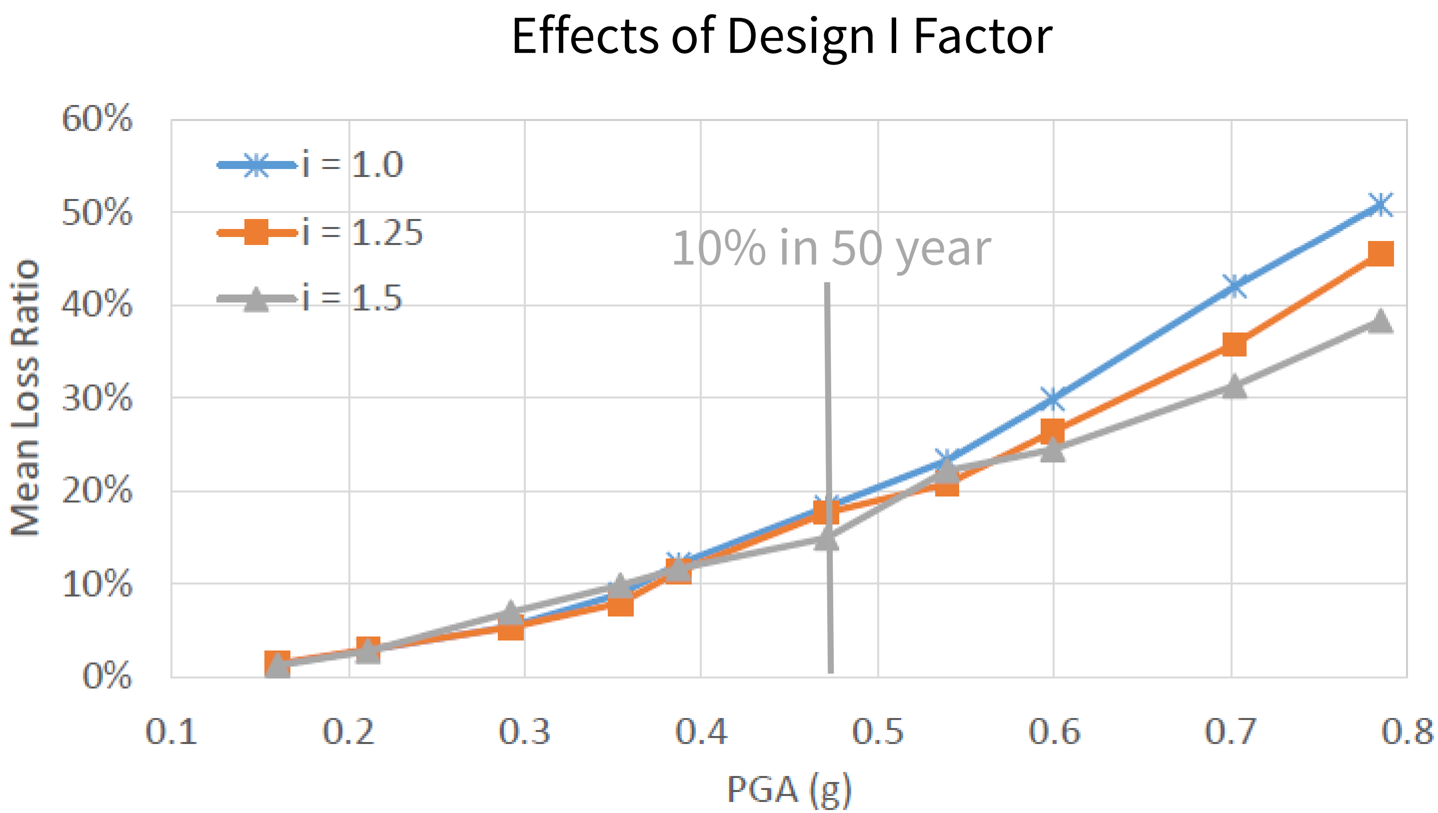


Figure 2 - Effects of Increased Design Strength (Ie > 1.0)

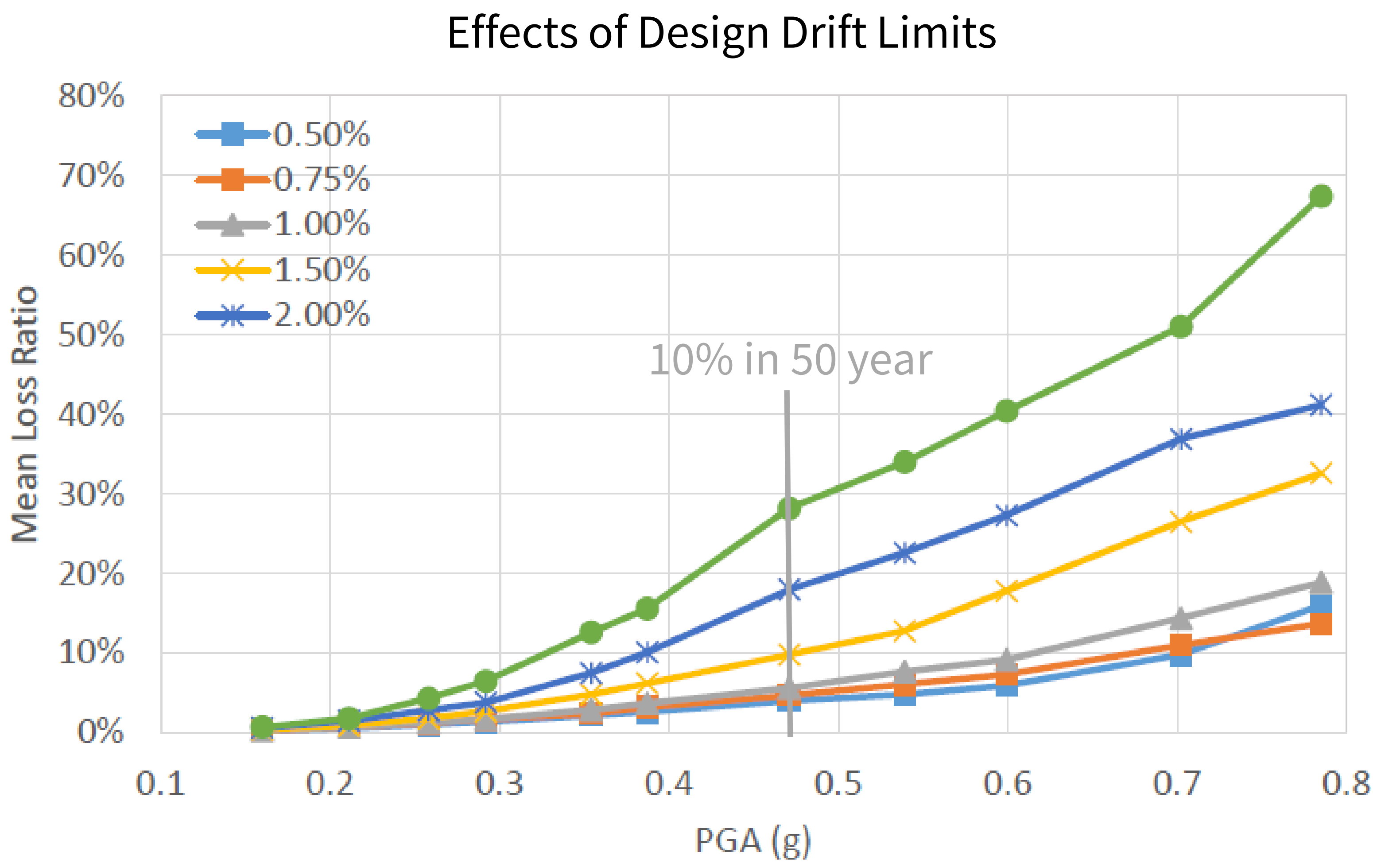


Figure 3 - Effects of Reducing Drift Limits

Effects of Risk Category IV (bracing, drift limits and strength)

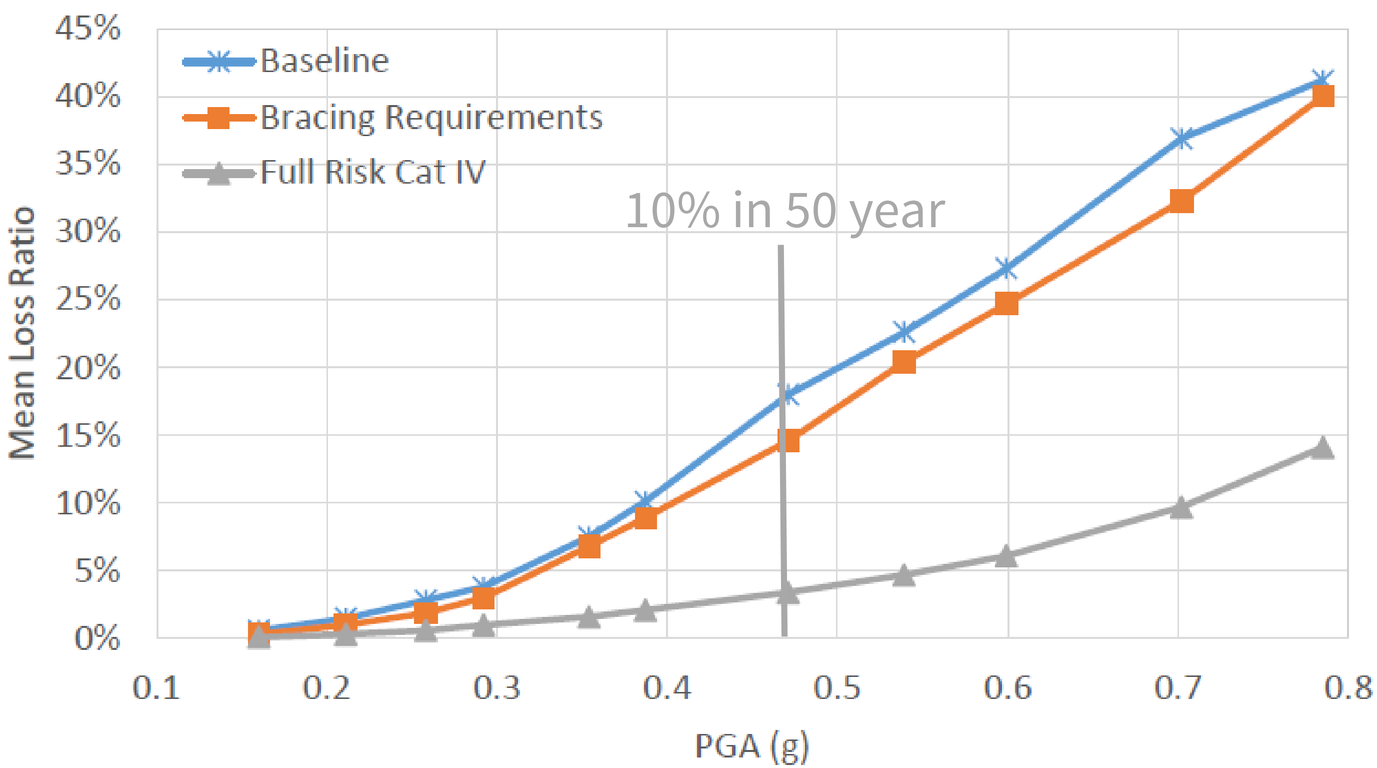


Figure 4 - Effects Risk Category IV Requirements

Summary of PBEE and RBEE

Design Aspect	Code Design	PBEE	RBEE
Design Objective	Safety (primarily)	Typically also only safety	Safety, reduced repair cost, reduced repair time

Summary of PBEE and RBEE

Design Aspect	Code Design	PBEE	RBEE
Design Objective	Safety (primarily)	Typically also only safety	Safety, reduced repair cost, reduced repair time
Codes and Guidelines	ASCE 7-10	LATBSDC, PEER TBI, ASCE 7-16, etc.	FEMA P-58, documents for acceptance criteria
Structural Modeling	Typically linear (ELF, RSA)	Typically nonlinear response-history	Often misunderstood that don't need NL RHA
Damage/Loss Modeling	None	None	FEMA P-58
Acceptance Criteria	Code rules	Rules to implicitly enforce safety	Safety (code+), repair cost limits, repair time limits

Summary of PBEE and RBEE

- We have talked about RBEE in the context of new design.
- It is equally applicable to other cases where you want information on damage, repair cost, and repair time (building closure time).
- Examples of recent projects using resiliency methods (using FEMA P-58):
  - ✓ Retrofit (cost/benefit)
  - ✓ Risk evaluations for mortgage (e.g. PML)
  - ✓ Risk evaluations for insurance
  - ✓ Risk evaluations for owners for special buildings (critical infrastructure, manufacturing, etc.)

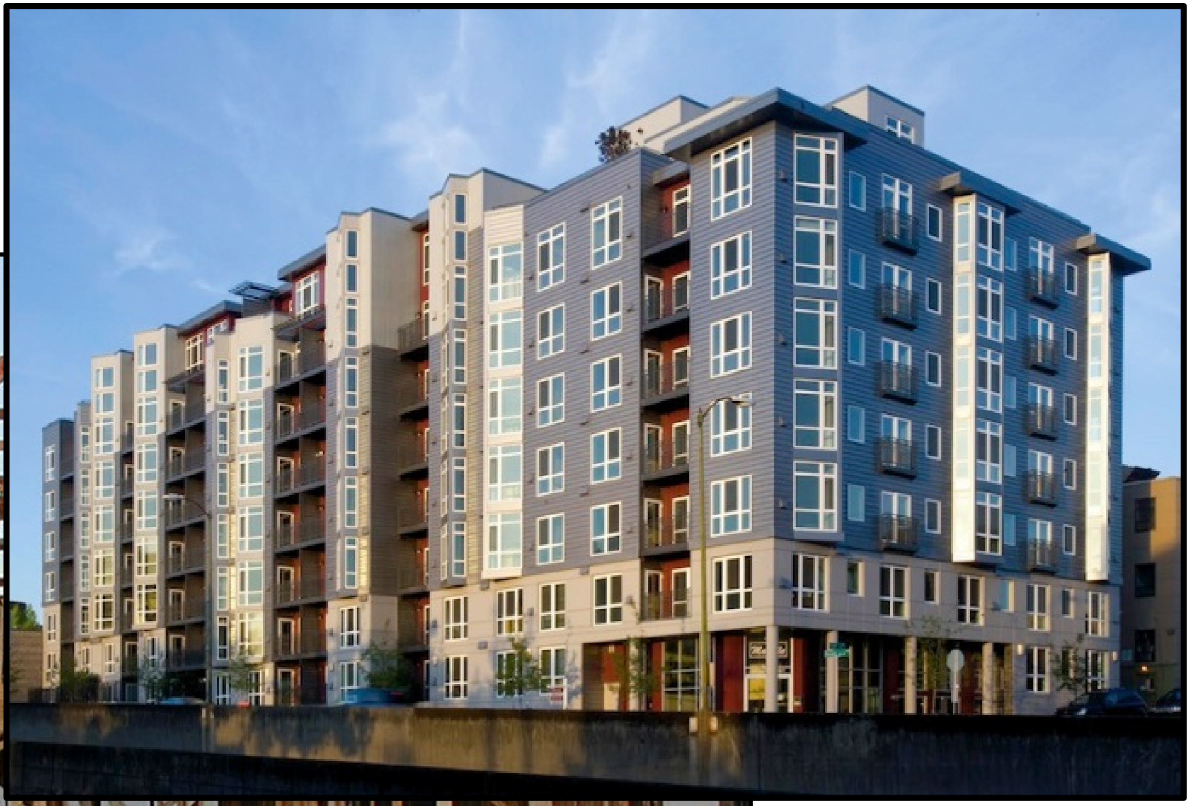
RBEE: Recent and Ongoing Research

- With $980k of funding from the National Science Foundation, we are also continuing further development for resilient design and advanced building-specific risk assessment.
- The research focuses are:
  - ✓ Make the methods cover all structural systems and conditions (already covers nearly all of them). Done with wood light-frame and working on tilt-up now.
  - ✓ Streamline the analysis so a nonlinear structural model (and response-history analysis) is typically not needed.

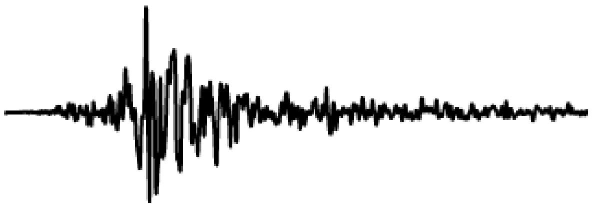
NSF

RBEE: Recent and Ongoing Research

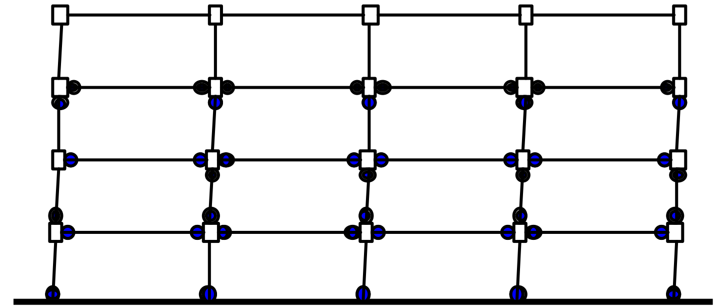
- Cover all structural systems:



RBEE: Recent and Ongoing Research



Ground Motion Hazard



Structural Responses

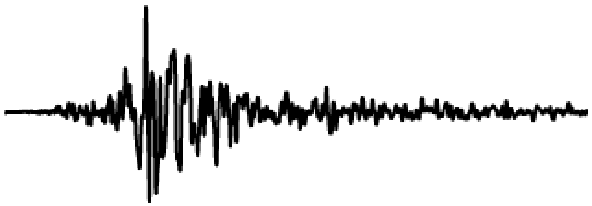
Component Damage

Casualties

Repair Time

Economic Loss

RBEE: Recent and Ongoing Research



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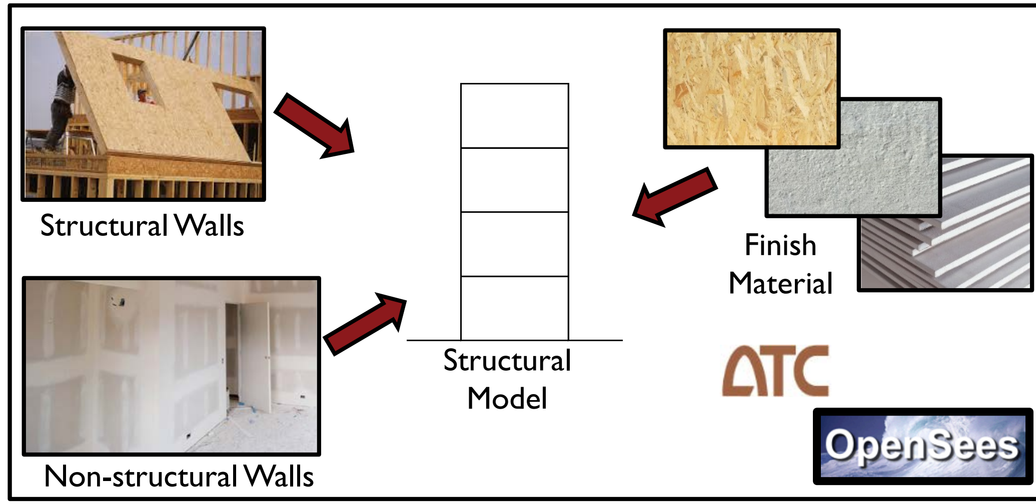

Structural Responses

Component Damage

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Economic Loss

RBEE: Recent and Ongoing Research

- Cover all structural systems:

- Streamline analyses by creating an SP3 Structural Response Prediction Engine ("we do the structural analysis for you").

OpenSees

RBEE: Recent and Ongoing Research

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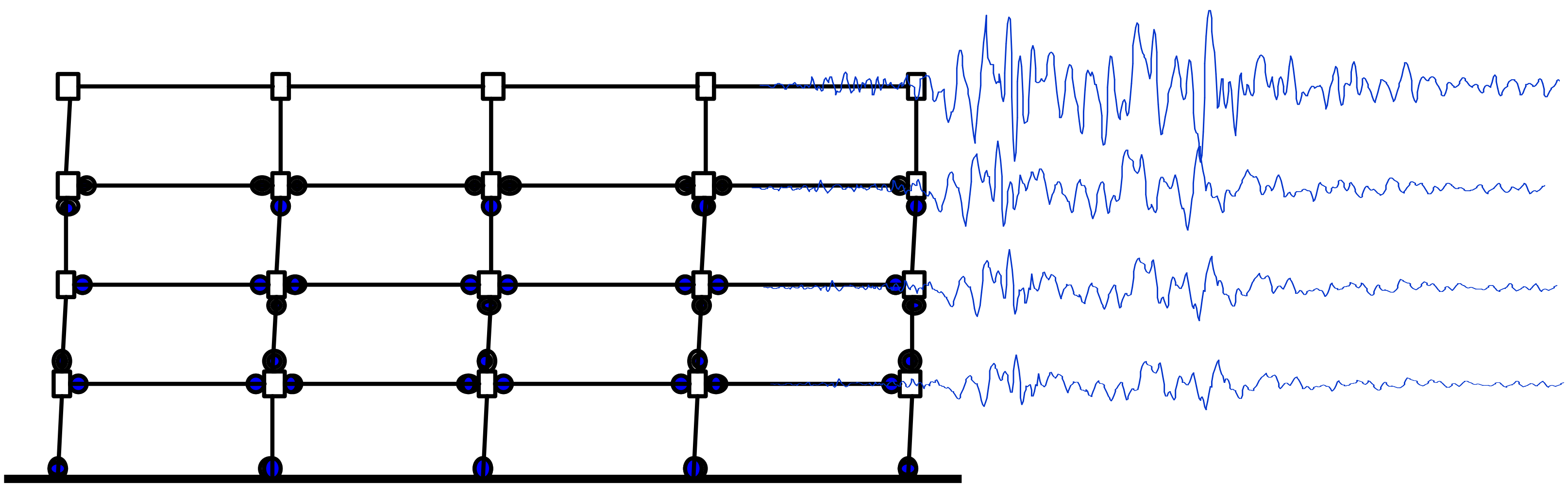
OpenSees



RBEE: Recent and Ongoing Research

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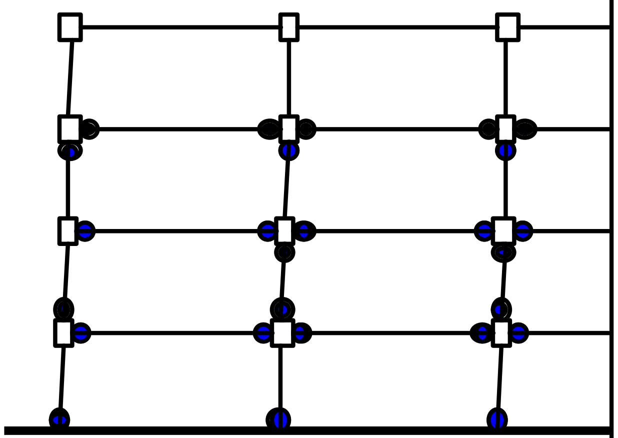

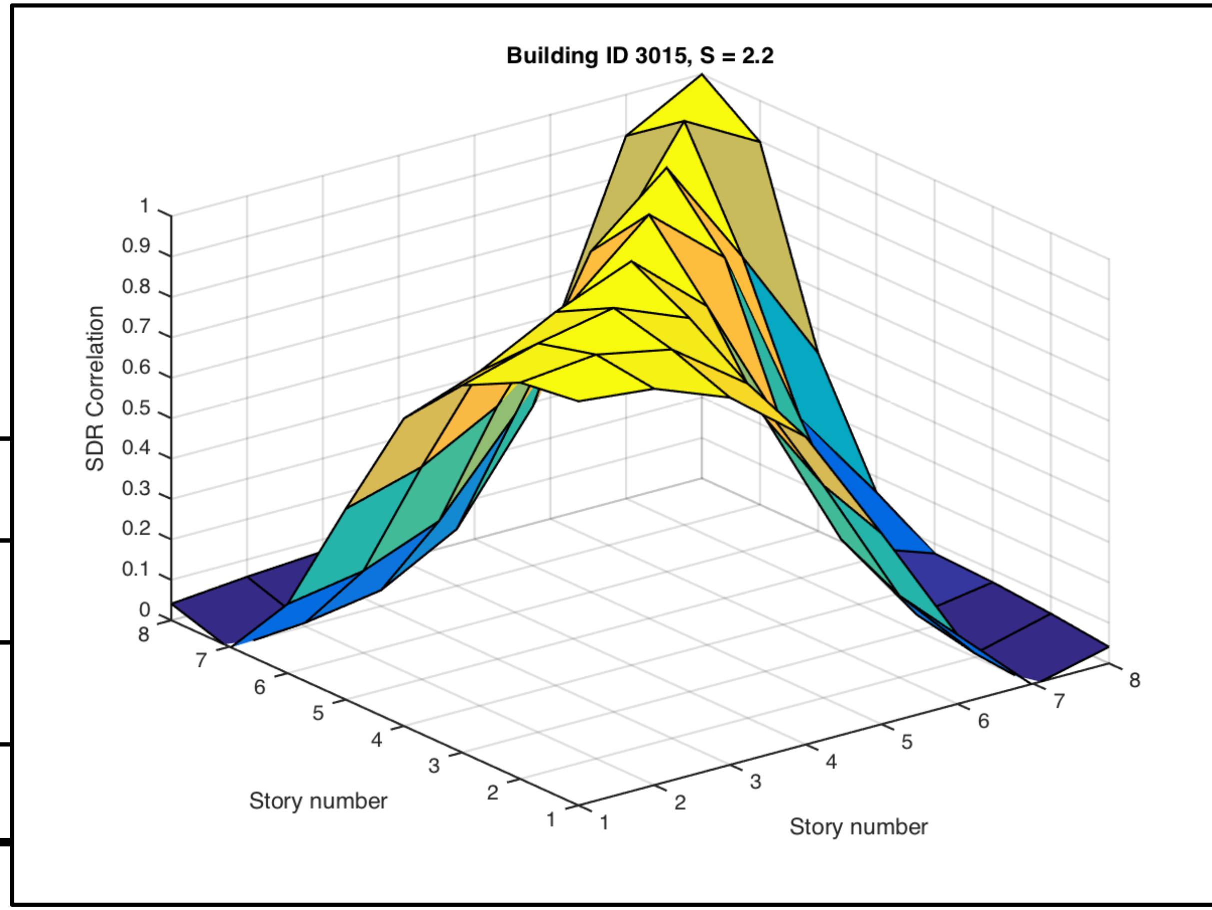

RBEE: Recent and Ongoing Research

SP3 Structural Response Prediction Engine

"We do the nonlinear response-history analysis for you."

Engineering Demand Parameters
for 100 ground motions
(drifts and floor accelerations)

Presentation Summary

- Overview of design methods
- Performance-Based and Resilience-Based Design
  - ✓ Design objective
  - ✓ Governing codes and guidelines
  - ✓ Structural modeling approach
  - ✓ Ground motion selection and scaling
  - ✓ Acceptance criteria
  - ✓ Recent project examples
- Recent and ongoing research to better enable Resilience-Based Design

Question: What are we going to do about this?

- **Cost:** Recent resilience-based design projects have estimated that resilient seismic performance **costed between 0-5%** of the project budget.
- **Performance Results:**
  - Repair cost of ~2% rather than ~10-20%.
  - Repair time of ~0 rather than ~6-24 months.
  - **With these methods, <u>we can design buildings that are not disposable</u>.

The Question for Us All:

With these resilience-based design methods now available, and with costs being reasonable, why wouldn't we do resilience-based design for <u>nearly all new buildings</u>?

Questions and Discussion

- Thank you for your time.
- Our goal is to support adoption of resilience-based design and risk assessment, and we welcome feedback and suggestions.
- Time for questions and discussion!

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