Using Performance-Based Earthquake Evaluation Methods to Assess the Relative Benefits of Different Structural Systems

PEER

Vesna Terzic

Sean K. Merrifield

Stephen A. Mahin

Pacific Earthquake Engineering Research Center

UC Berkeley

OpenSees Days 2012

What are earthquake engineers generally trying to accomplish?

Preserve Life Safety and Prevent Collapse!

PEER

Building codes are minimum standards for public safety

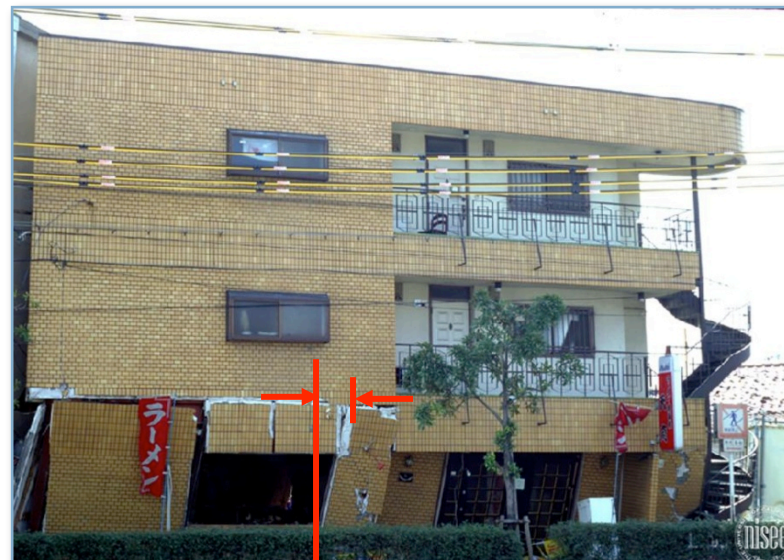
- Stated purpose:
  - Provide minimum provisions for design and construction of structures to resist effects of seismic ground motions
  - "…to safeguard against major structural failures and loss of life, not to limit damage or maintain function."

Designed to protect life in extreme event, but damage expected

PEER

Building codes do not provide earthquake proof structures

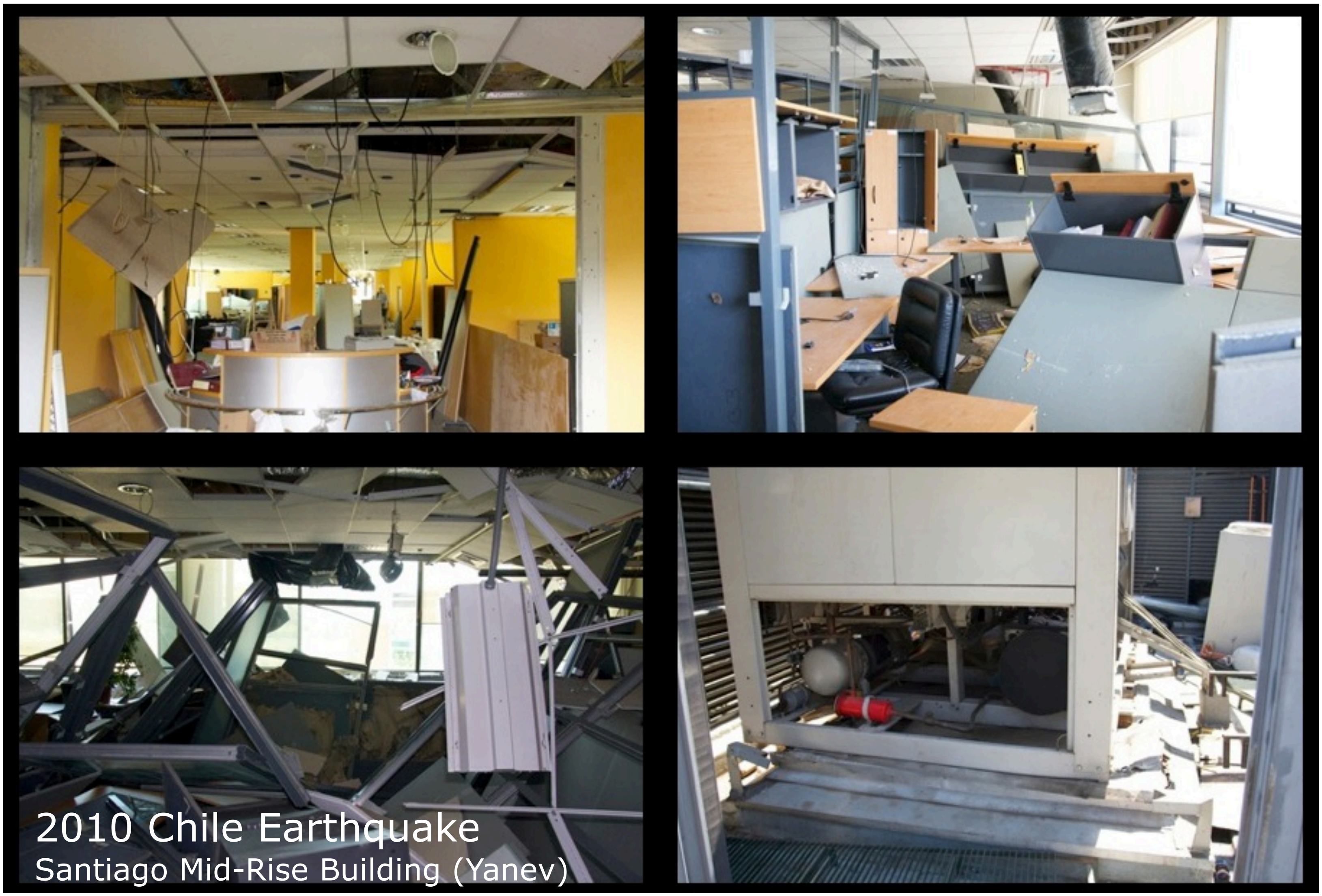
- Stated purpose:
  - Provide minimum provisions for design and construction of structures to resist effects of seismic ground motions
  - "…to safeguard against major structural failures and loss of life, not to limit damage or maintain function."



Designed to protect life in extreme event, but damage expected

PEER

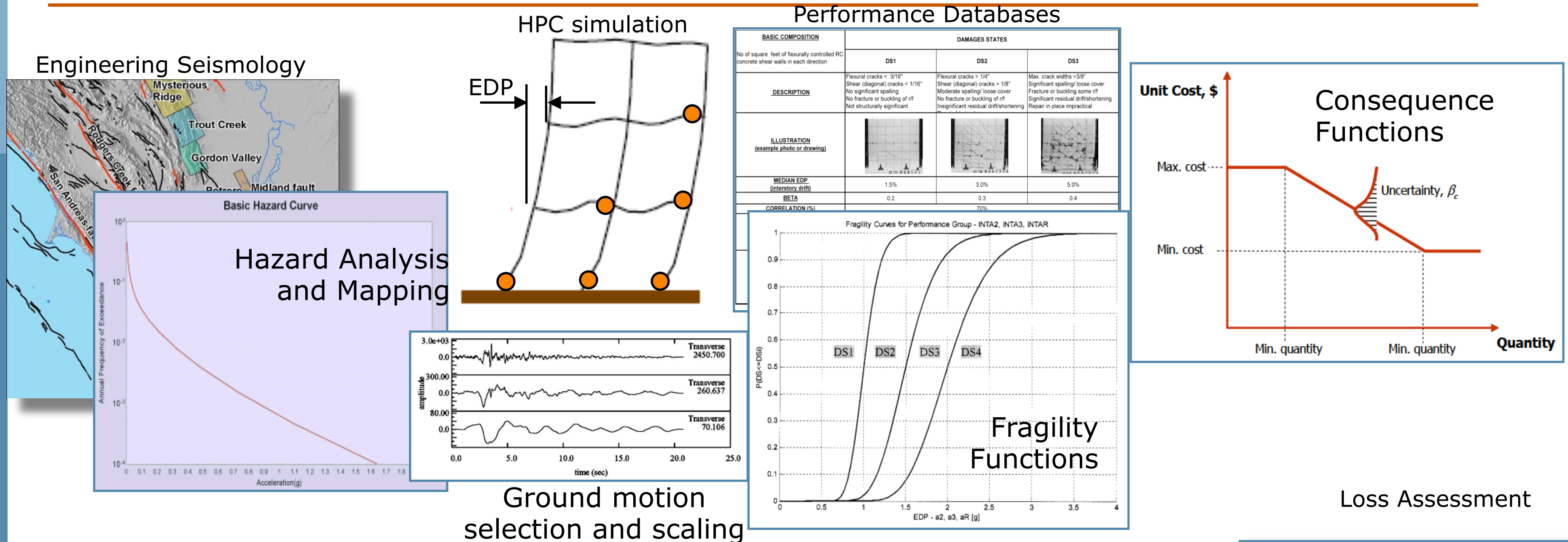
Nonstructural Elements Threaten Life Safety, and Damage is Disruptive and Expensive



2010 Chile Earthquake
Santiago Mid-Rise Building (Yanev)

PEER

Holistic risk-oriented view:
Performance-Based Seismic Design



Loss Assessment

Seismic Hazard Analysis	→	Response Analysis	→	Damage Analysis	→	Loss Analysis
$\lambda(im)$		$G(edp \mid im)$		$G(dm \mid edp)$		$G(dv \mid dm)$
IM: intensity measure		**EDP**: Engineering Demand Parameter		**DM**: Damage Measure		**DV**: Decision Variable

$$\lambda(DV > dv) = \int_{im} \int_{dm} \int_{edp} G(dv \mid dm)\, dG(dm \mid edp)\, dG(edp \mid im) \left| d\lambda(im) \right|$$

Probabilistic Assessment of:
- ✓ Cost of repair and loss of function
- ✓ Downtime
- ✓ Casualties
- ✓ *Embodied energy*

Consider performance from three perspectives

- Structural response
- Losses caused by scenario events
- Expected life cycle costs

PEER

PBEE of different structural systems

- Three storey steel office building
- Located in Oakland, California (soil type D)
- Two lateral-load resisting systems:
  - Special Moment Resisting Frame (SMRF)
  - Base-isolated Intermediate Moment Resisting Frame (BI-IMRF) with 4 alterations considering:
    - Two bearing designs (TFP bearings)
    - Two superstructure designs
- SMRF and BI-IMRF (baseline case) are designed by professional engineers based on ASCE 7 (2005) to satisfy minimum code requirements.

PEER

Alterations of BI-IMRF

1. S1-ID1 (baseline case): Code based design of both isolators and superstructure
2. S1-ID2: Superstructure of the baseline case, isolators are improved
3. S2-ID1: Isolators of the baseline case, superstructure improved
4. S2-ID2: superstructure and isolators are improved

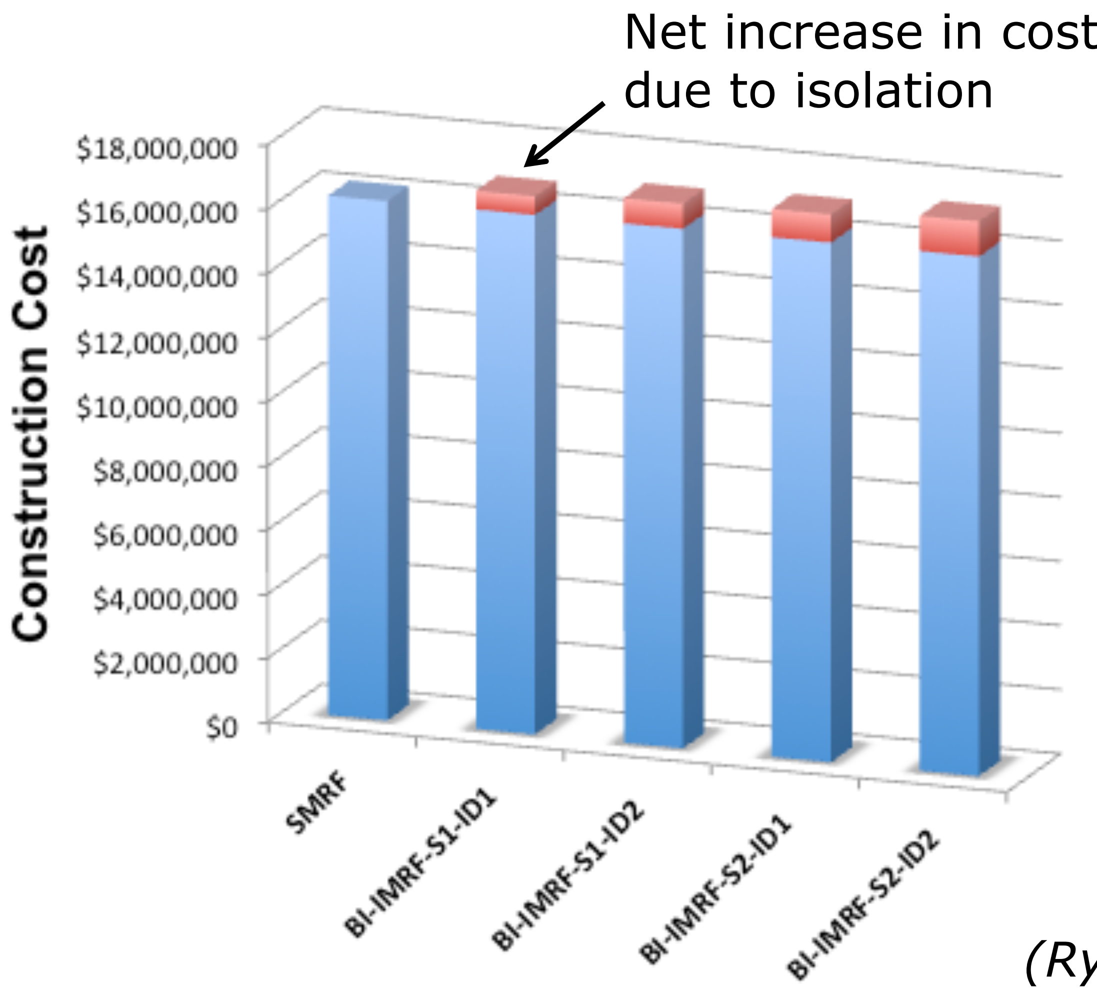
PEER

Loss Analysis

- Two loss metrics (DVs) are used to assess the effectiveness of the structural system
  - Business downtime
  - Financial loss (repair cost & revenue losses)
- Two types of assessments are performed:
  - Hazard-based assessments
  - Time-based assessments
    - ➡ annualized losses
    - ➡ return on investments

PEER

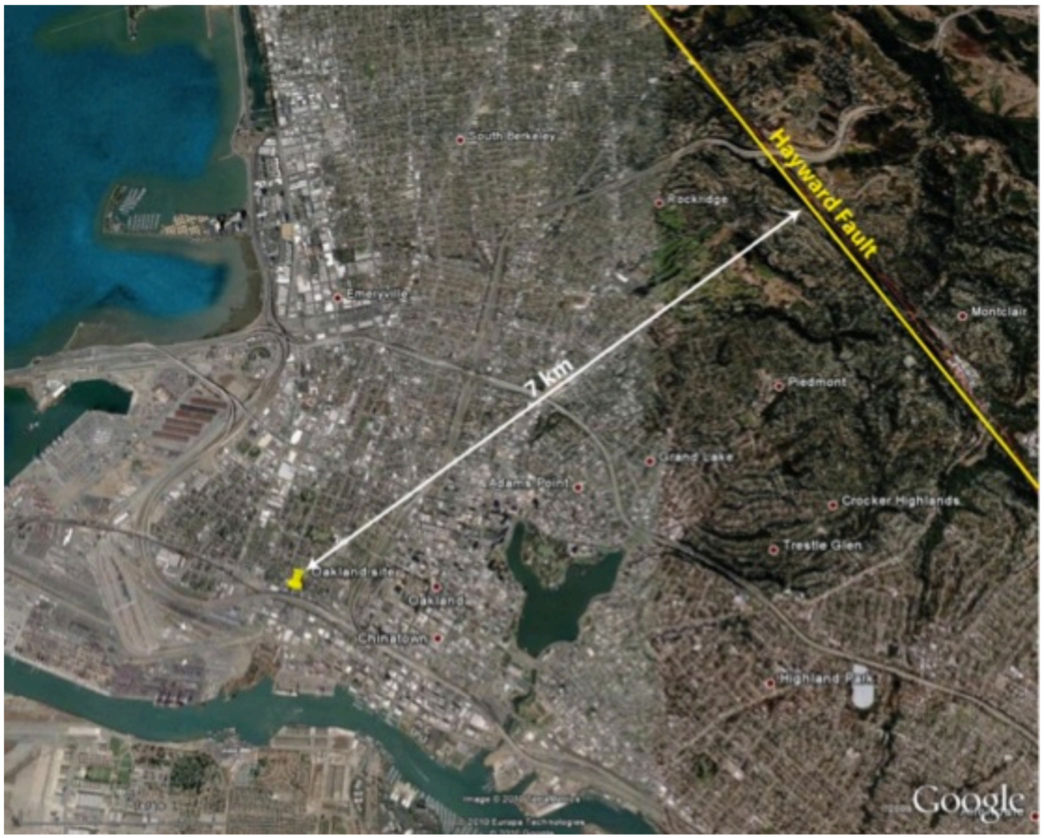
Construction Building Costs



(Ryan et al., 2009)

PEER

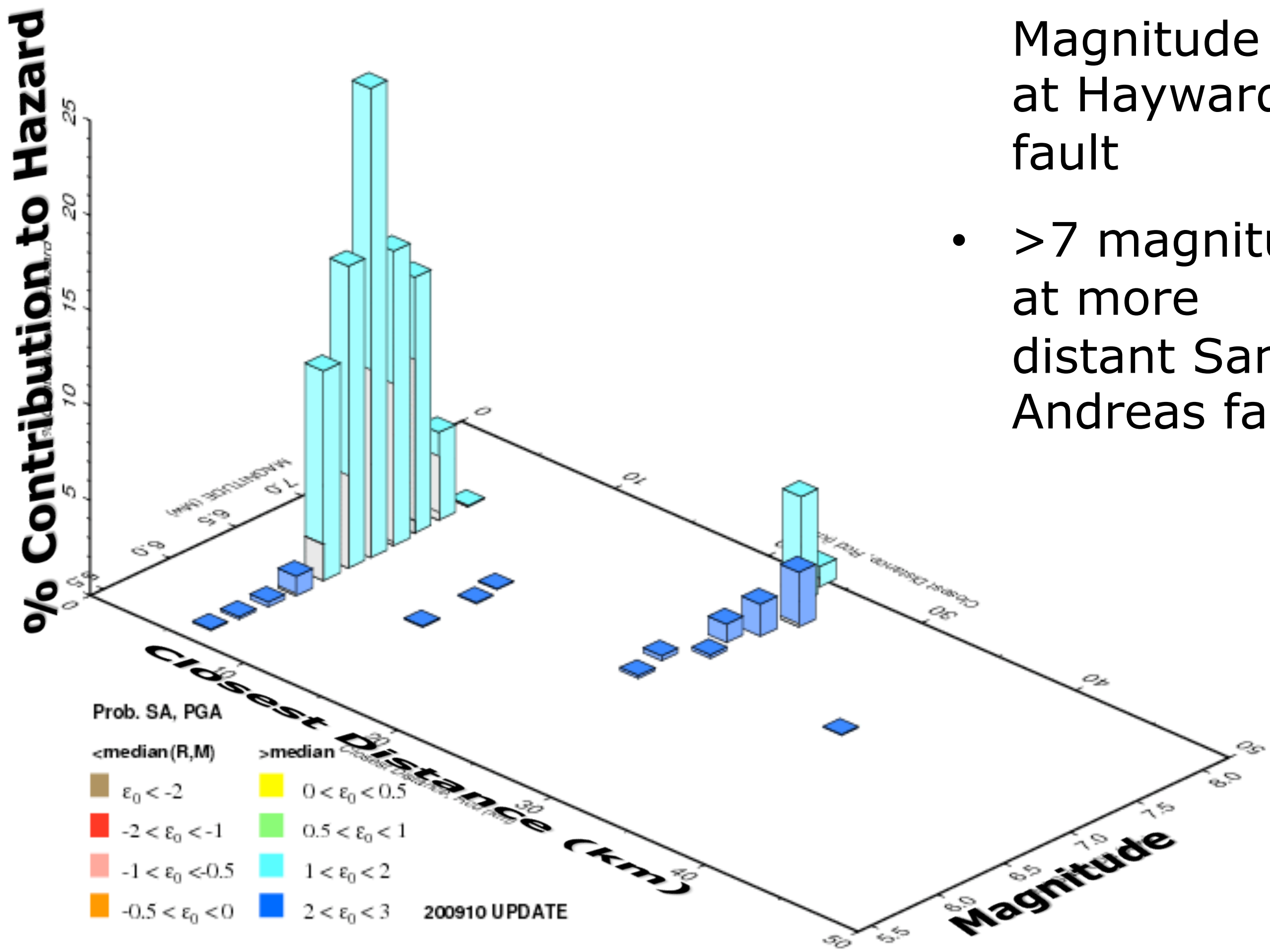
Building Site – Oakland, California



Located about 7 km from Hayward Fault (strike slip mechanism)

PEER

De-aggregation of site – T_R=2475 years



- Dominated by Magnitude 7 at Hayward fault
- >7 magnitude at more distant San Andreas fault

Expected ground motions at site

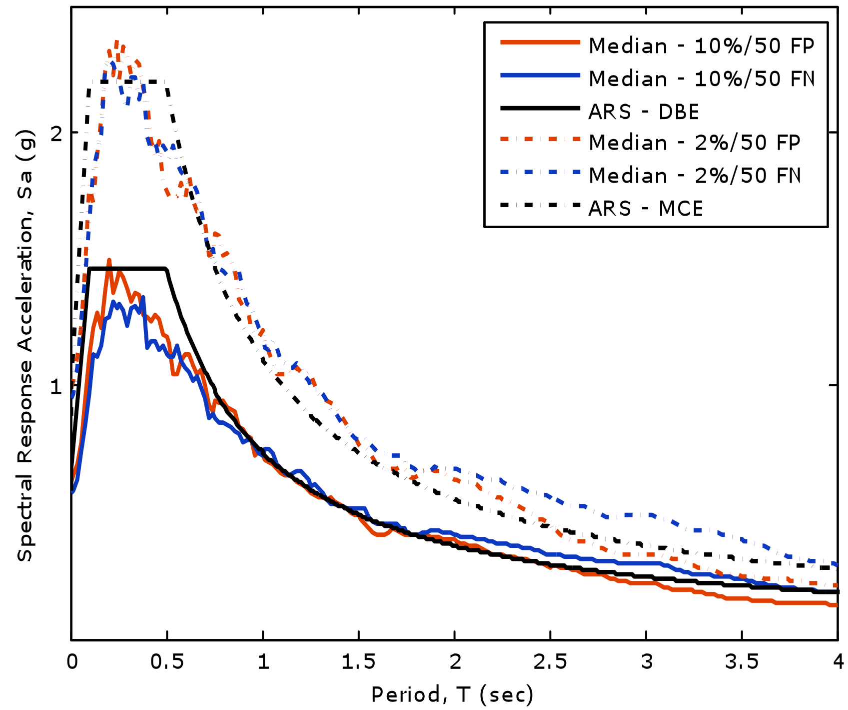
Based on de-aggregated hazards, 40 records were selected for three hazard level:

•50%/50-years (T_R=72 years)

•10%/50-years (T_R=474 years)

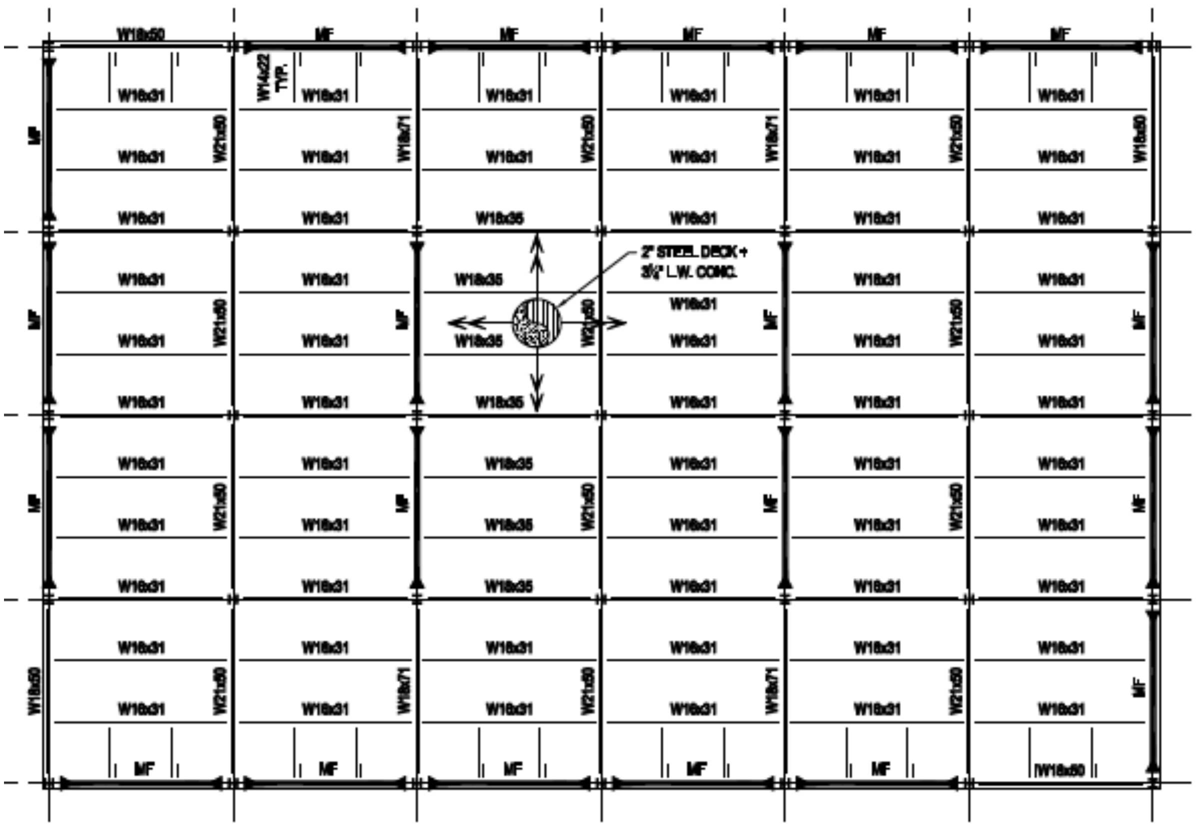
•2%/50-years (T_R=2475 years)

Baker, et al, PEER report 2011/3



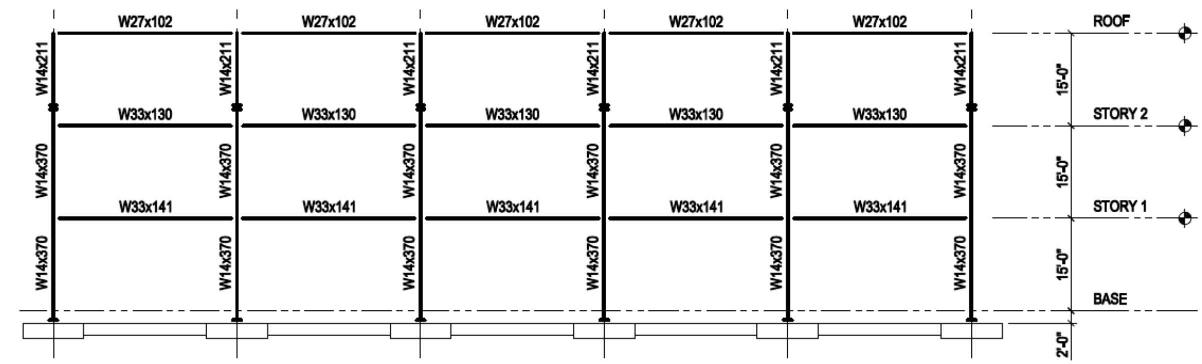
PEER

Archetype Building – Plan View

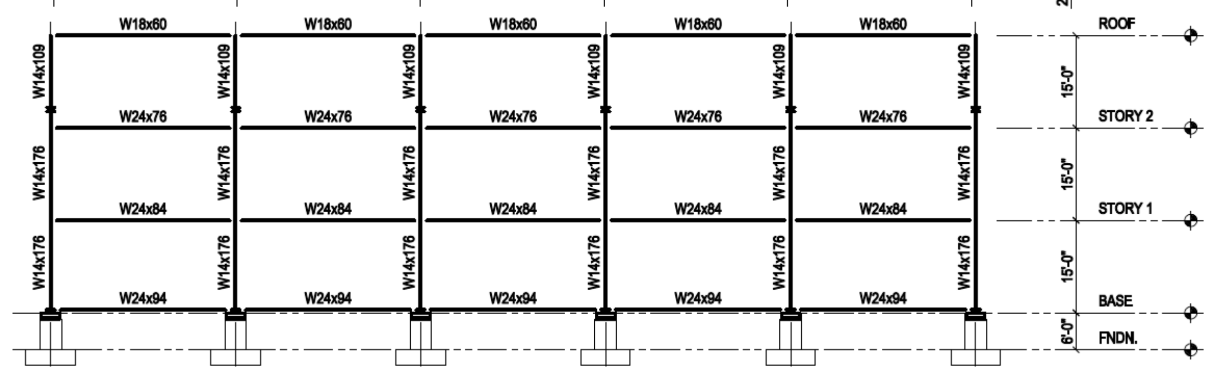


- 6 x 4 bay building
- Lateral-load resisting system at the building perimeter
- Bay spacing = 30 ft
- Storey Height = 15 ft

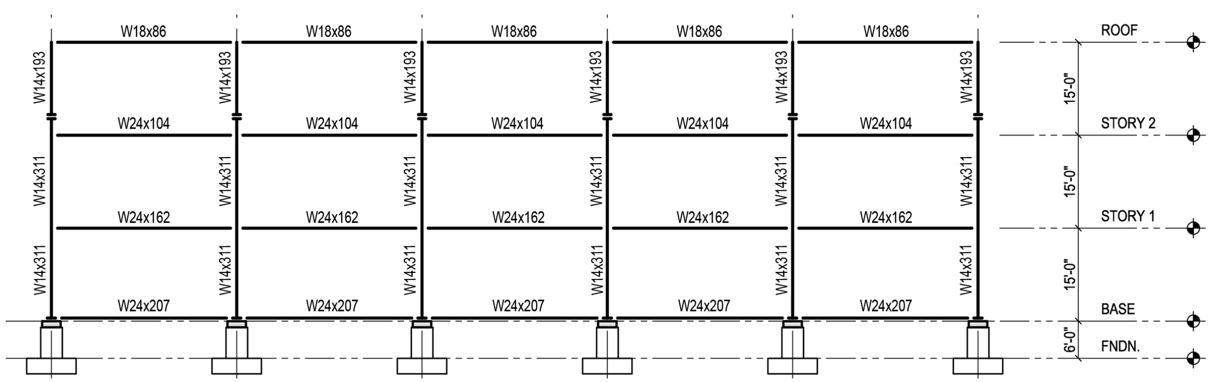
Buildings considered



SMRF



BI-IMRF-S1

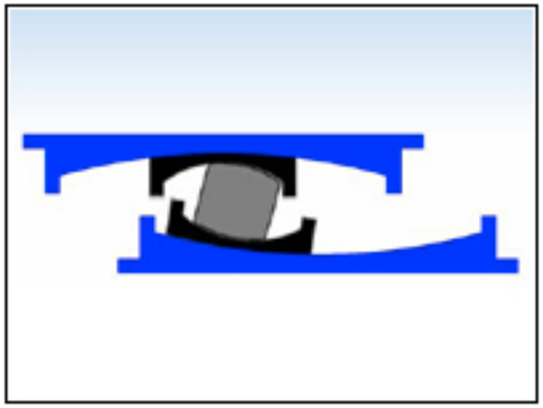


BI-IMRF–S2

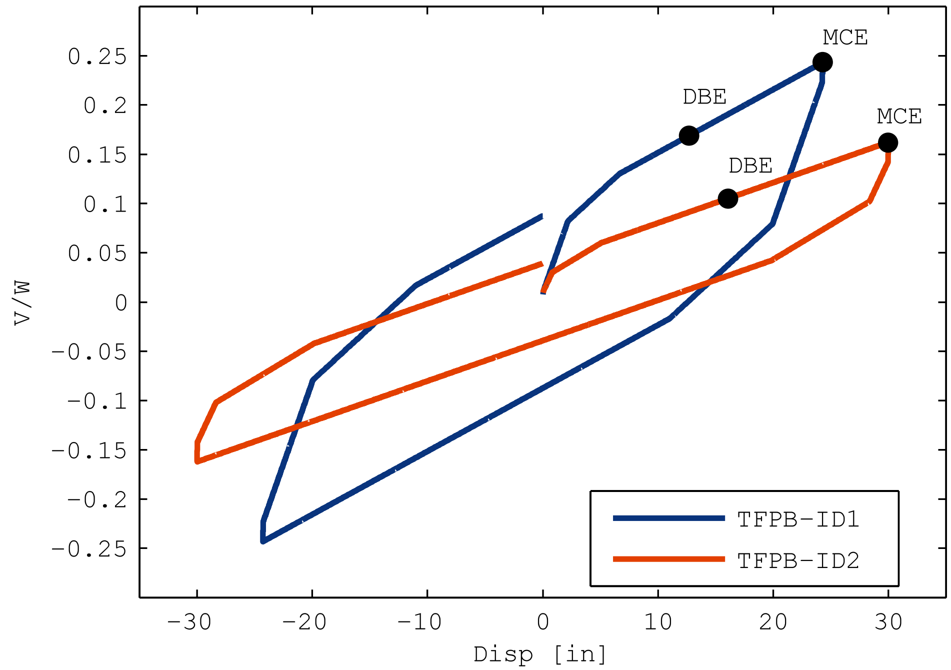
PEER

Two Design of Isolation Systems

Triple Friction Pendulum Bearings



Isolator Properties	DBE		MCE	
	ID1	ID2	ID1	ID2
Effective period	2.77 sec	3.95 sec	3.07 sec	4.35 sec
Effective damping	24.2 %	22.9 %	15.8 %	15.1 %
Isolator displacement	12.7 in.	16.1 in.	24.3in.	30 in.



PEER

Numerical Model and Methods

- Analysis performed with OpenSees
- THA performed on 2D frames
- Load:
  - gravity loads
  - vertical and horizontal component of excitation
- Leaning column was modeled to account for P-Δ effects from the gravity columns
- Beams and columns modeled with nonlinear force-based fiber elements with low-cycle fatigue failure capabilities
  - Except for beams of SMRF with RBS connections, modeled with rotational spring – elastic element – rotational spring assembly.

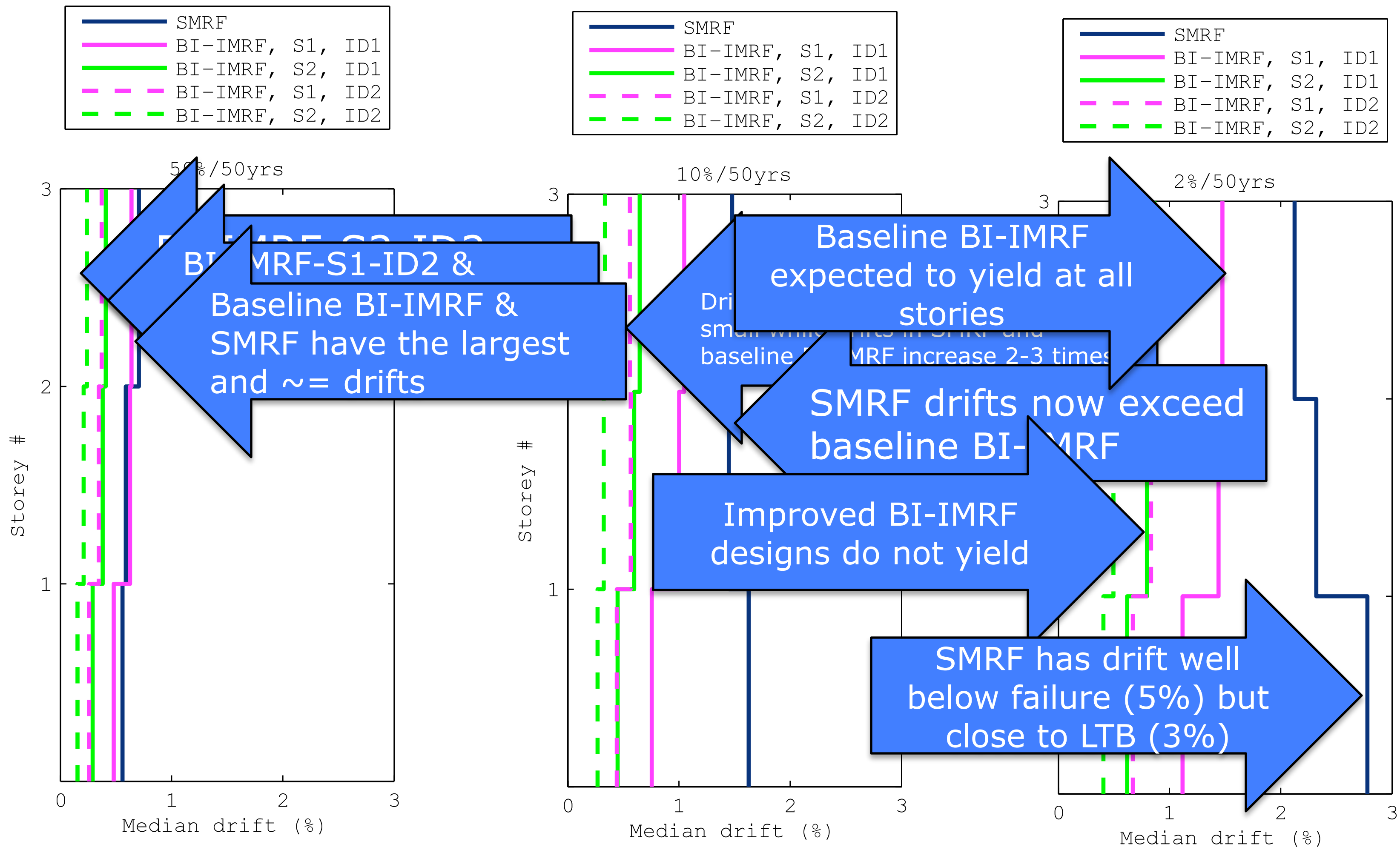
PEER

Numerical Model and Methods

- Isolators are modeled with zeroLength elements (horizontal springs) and tri-linear model
- Panel zone regions are modeled with elastic elements (recommended by ATC/PEER-72)
- Geometric nonlinearity is accounted for utilizing P-Δ transformation
- Damping modeled with damping ratio of 3%:
  - SMRF: Mass and tangent stiffness proportional
    - based on T_1 and T_3 for 50%/50-year hazard level
    - based on $1.5T_1$ and T_3 for DBE and MCE hazard levels
  - BI-IMRF: Tangent stiffness proportional
    - based on T_1 for 50%/50-year hazard level
    - based on the appropriate T_{eff} for DBE and MCE hazard levels

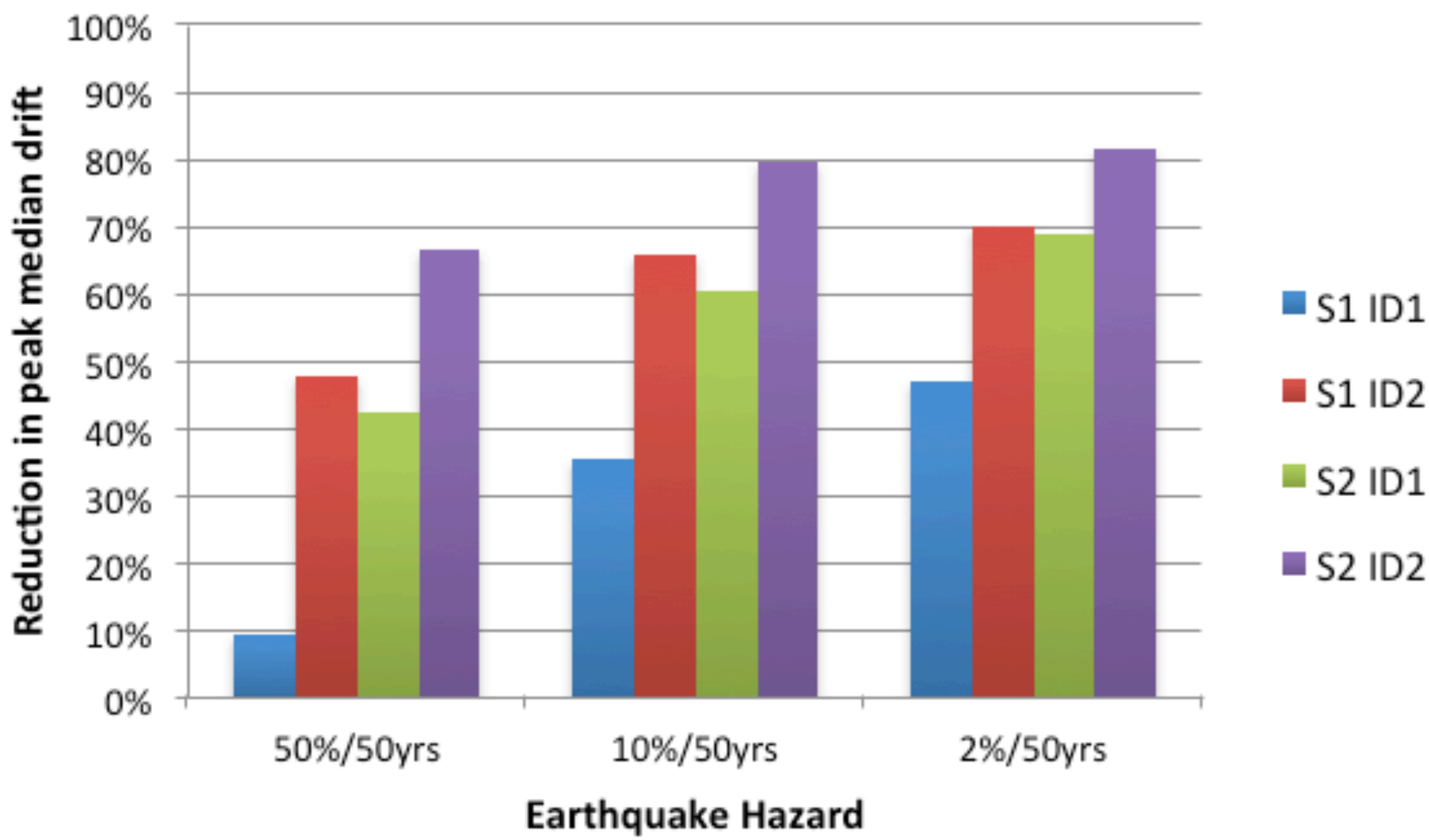
PEER

Structural Response:
Median Story Drift



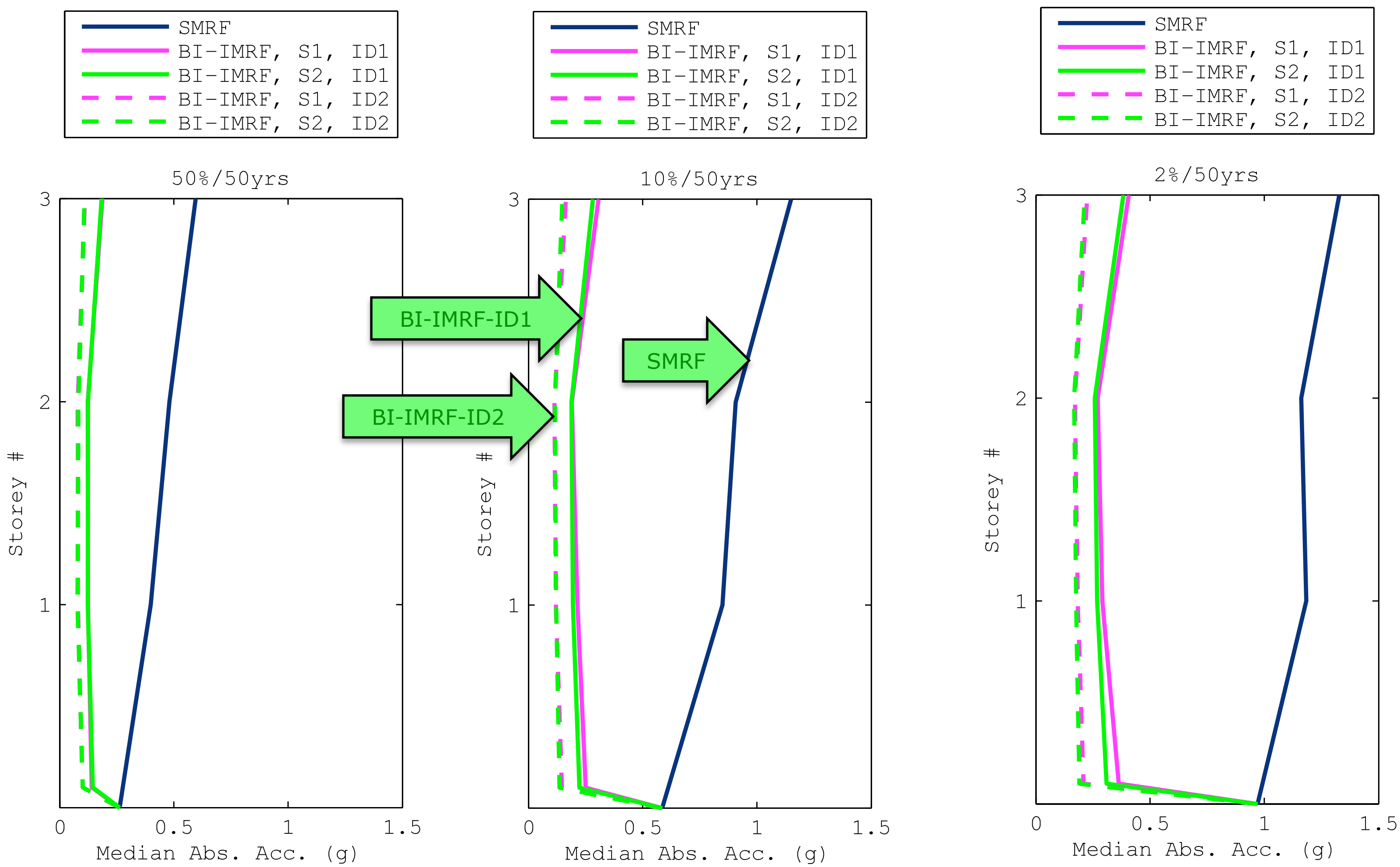
Structural Response:

Reduction in Peak Median Storey Drift of BI-IMRF systems compared to SMRF



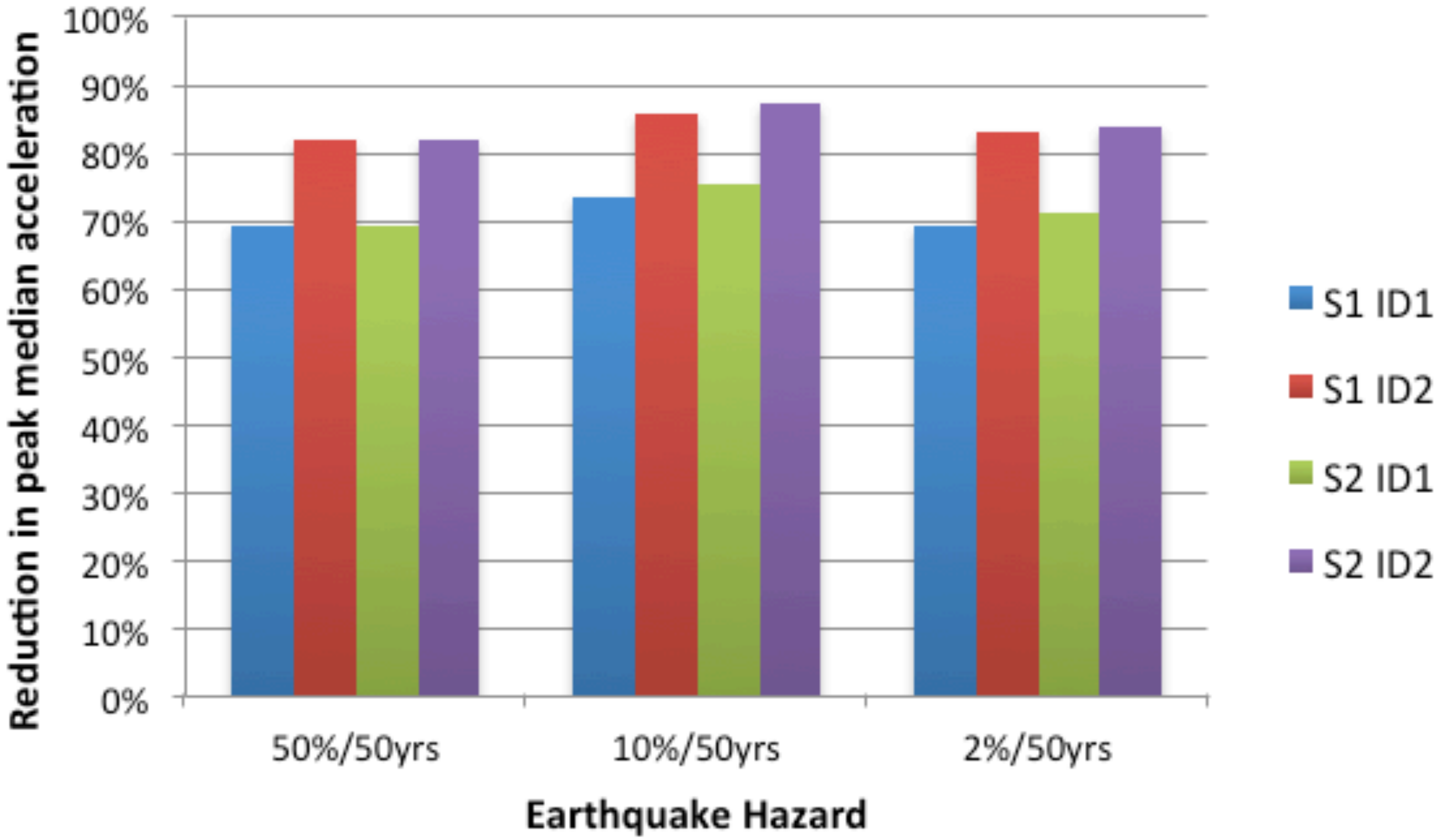
PEER

Structural Response:
Median Floor Accelerations



Structural Response:

Reduction in Peak Median Floor Acceleration of BI-IMRF systems compared to SMRF



PEER

Summary: Structural Response

- **SMRF:**
  - Relatively large drifts at all levels of excitation
  - Yielding starts at DBE hazard level, nonstructural damage triggered at 50%/50yrs hazard level
  - Relatively large accelerations at all levels of excitation, nonstructural damage triggered at 50%/50yrs hazard level
  - Amplification of acceleration along the height
- **Baseline BI-IMRF:**
  - Relatively large drifts (9% (FE), 35% (DBE) & 47%(MCE) reduction compared to SMRF)
  - Yielding starts at MCE hazard level, nonstructural damage triggered at 50%/50yrs hazard level
  - Low accelerations (70% reduction compared to SMRF)
  - Almost uniform acceleration along the height
- **BI-IMRF-S1-ID2 (with improved isolation system)**
  - Relatively small drifts at all levels of excitation (47% (FE), 65% (DBE) & 70%(MCE) reduction compared to SMRF)
  - No yielding, nonstructural damage of drift sensitive components triggered at DBE hazard level
  - Low accelerations (82% reduction compared to SMRF)
  - Almost uniform acceleration along the height
- **BI-IMRF-S2-ID1 (with improved superstructure)**
  - Relatively small drifts at all levels of excitation (42% (FE), 60% (DBE) & 69%(MCE) reduction compared to SMRF)
  - No yielding, nonstructural damage of drift sensitive components triggered at DBE hazard level
  - Low accelerations (70% reduction compared to SMRF)
  - Almost uniform acceleration along the height
- **BI-IMRF-S2-ID2 (with improved superstructure & isolation system)**
  - Very small drifts at all levels of excitation (66% (FE), 80% (DBE) & 82%(MCE) reduction to SMRF)
  - No yielding, nonstructural damage of drift sensitive components triggered at MCE hazard level
  - Low accelerations (82% reduction compared to SMRF)
  - Almost uniform acceleration along the height

Loss Analysis

- Two loss metrics (DVs) are used to assess the effectiveness of the structural system
  - Business downtime
  - Financial loss (repair cost & revenue losses)
- Two types of assessments are performed:
  - Hazard-based assessments
  - Time-based assessments
    - ➡ annualized losses
    - ➡ return on investments

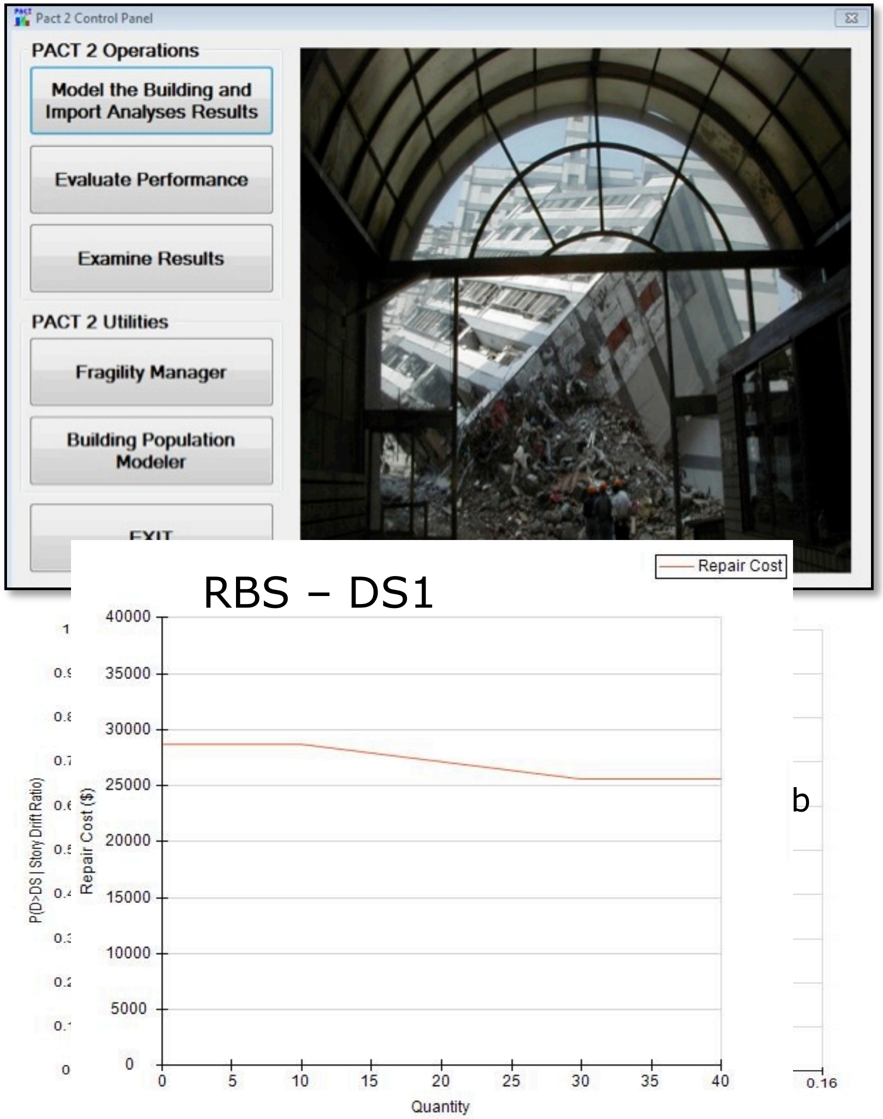
PEER

Hazard-based assessments

- Performance Assessment Computation Tool (PACT 2) is used to calculate:
  - Repair cost of the system for each hazard level
  - Repair time of each damaged component
- The authors of the work developed a method for calculating business downtime considering the order of building repairs and accounting for mobilization factors (e.g., building inspection, permitting, financing)

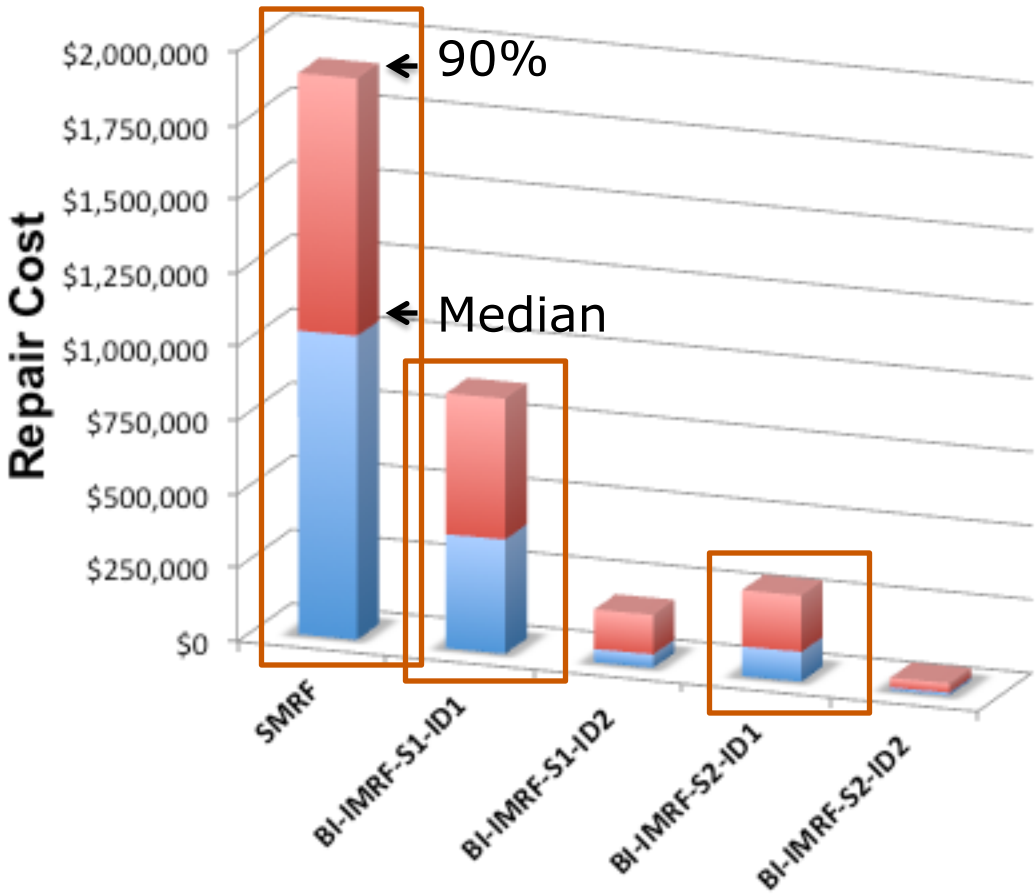
PEER

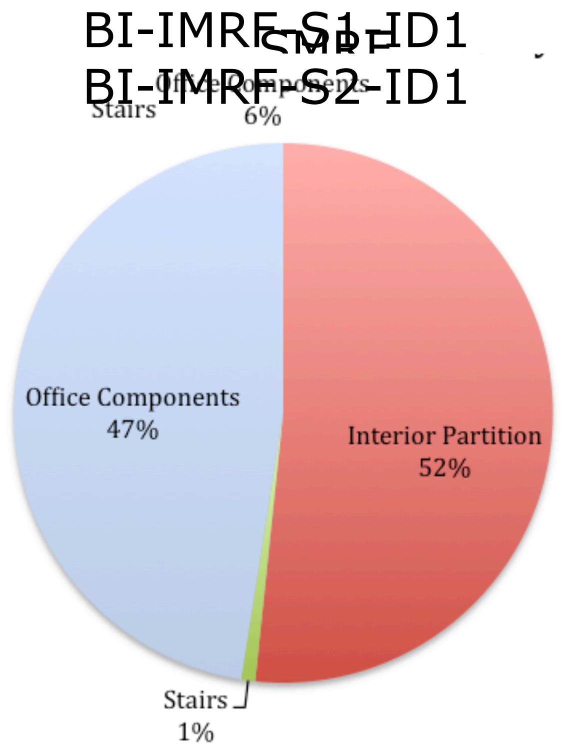
Intro to PACT 2



- FEMA/ATC-58 product based on PEER PBEE Methodology
- Modeling process is broken into three stages:
  - Provide building information
  - Define structural and nonstructural components as well as content (including quantities for each component)
  - Input EDPs for each ground motion and each hazard level
- $\boxed{\text{EDP}}$-$\boxed{\text{DM}}$-$\boxed{\text{DV}}$ (direct financial losses)
- Uses Monte Carlo method to take into account various uncertainties (within the modeling process, component quantities, loss assessment)

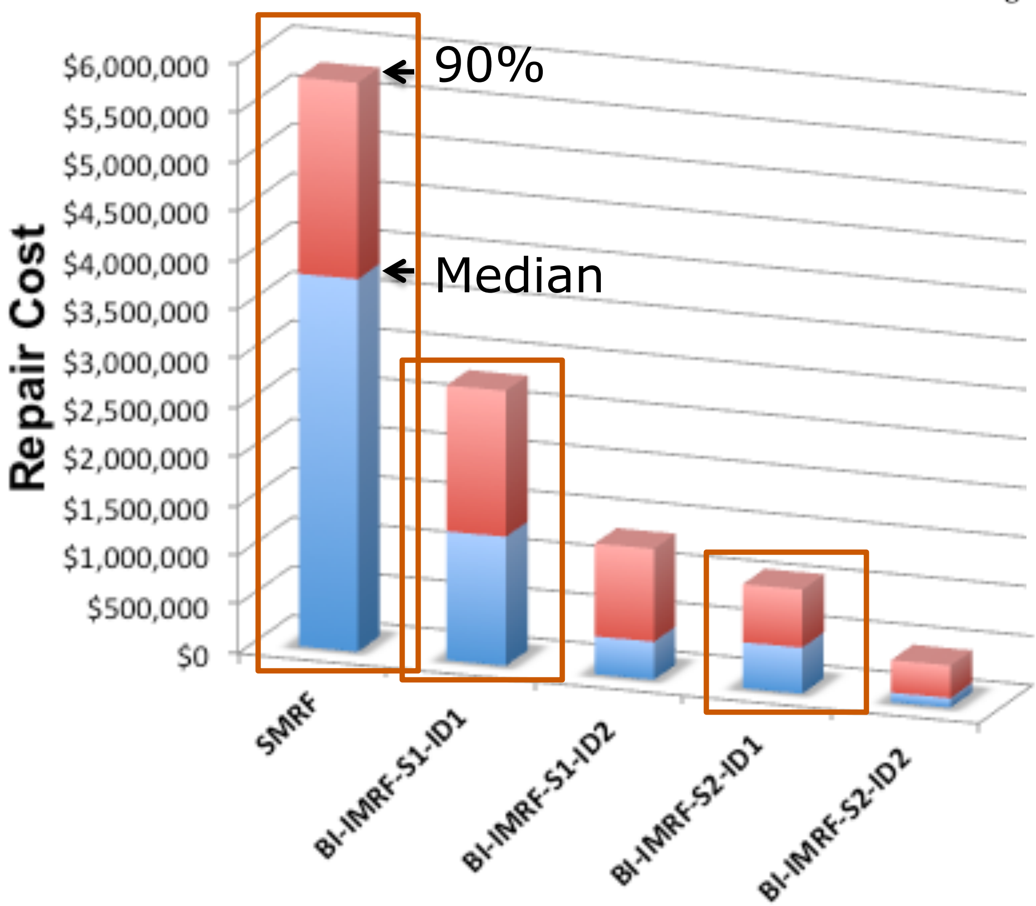
Repair Costs for scenario events:
Frequent Earthquakes (50%/50-yrs)

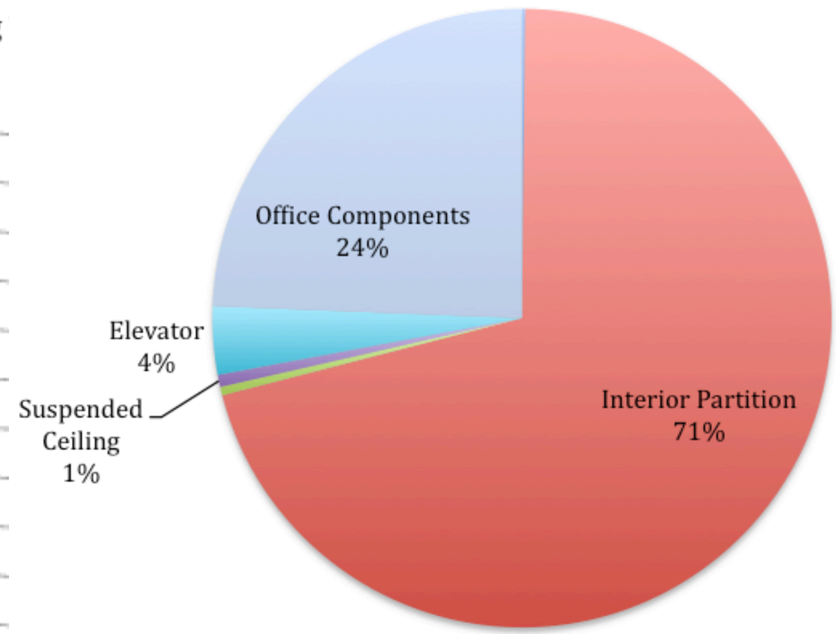




PEER

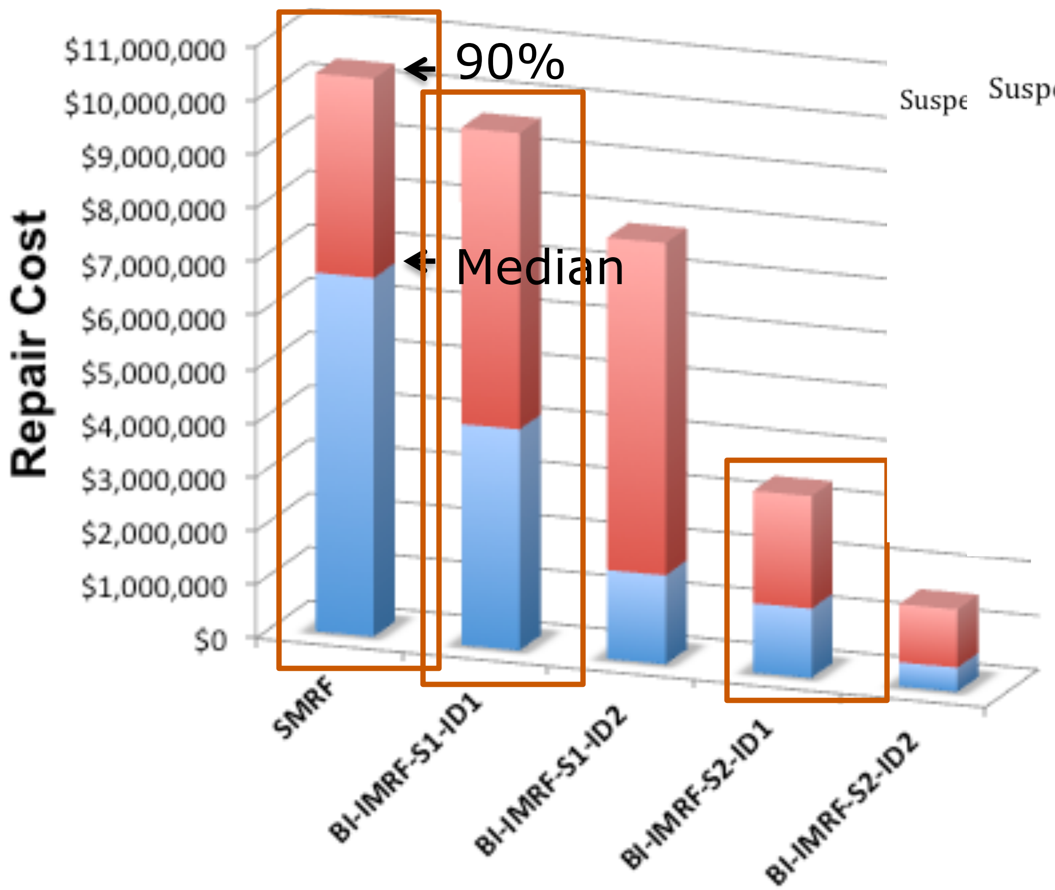
Repair Costs for scenario events:
Design Basis Earthquakes (10%/50-yrs)

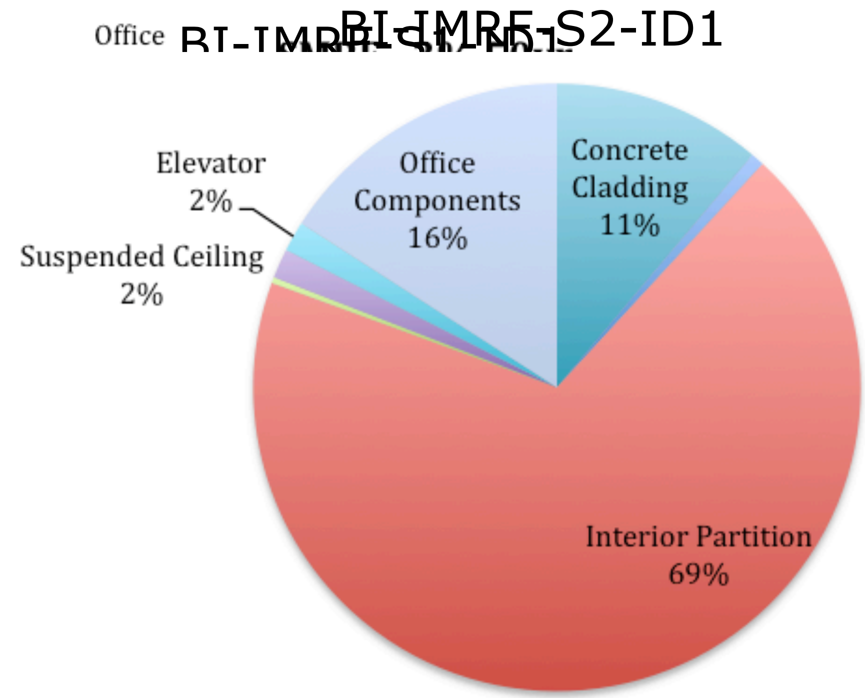




PEER

Repair Costs for scenario events:
Maximum Credible Earthquakes (2%/50-yrs)



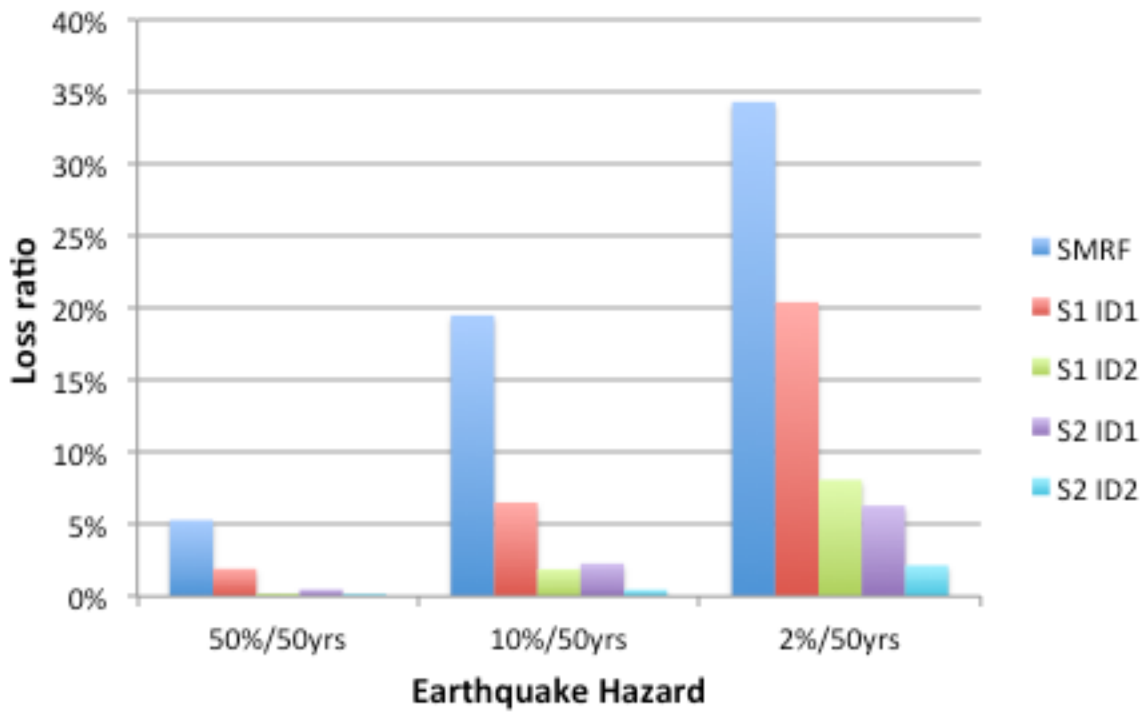


PEER

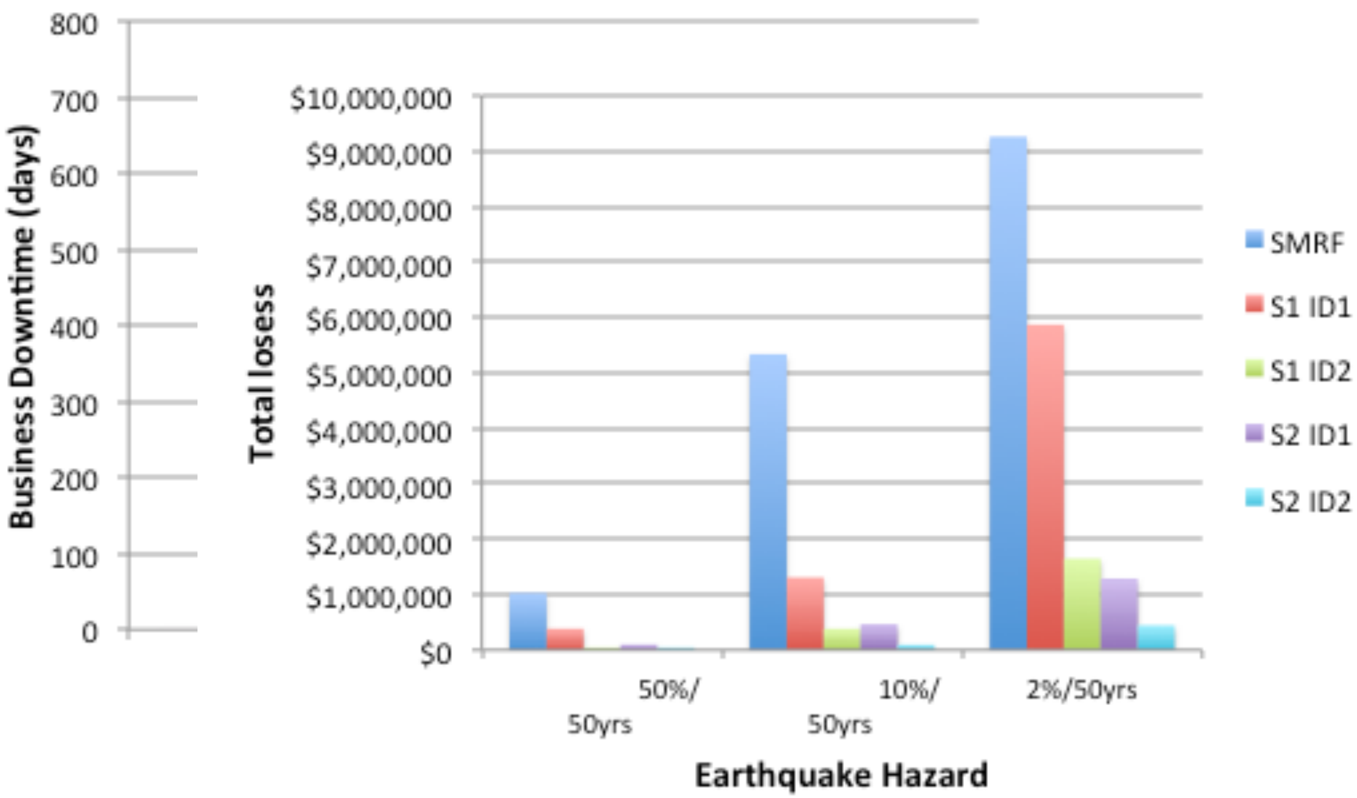
Repair Costs for scenario events:
Loss Ratio

$$\text{Loss Ratio} = \frac{\text{Repair Cost}}{\text{Total Cost}}$$

Total Cost = 1.2 x Construction Cost



Business Downtime & Total Losses

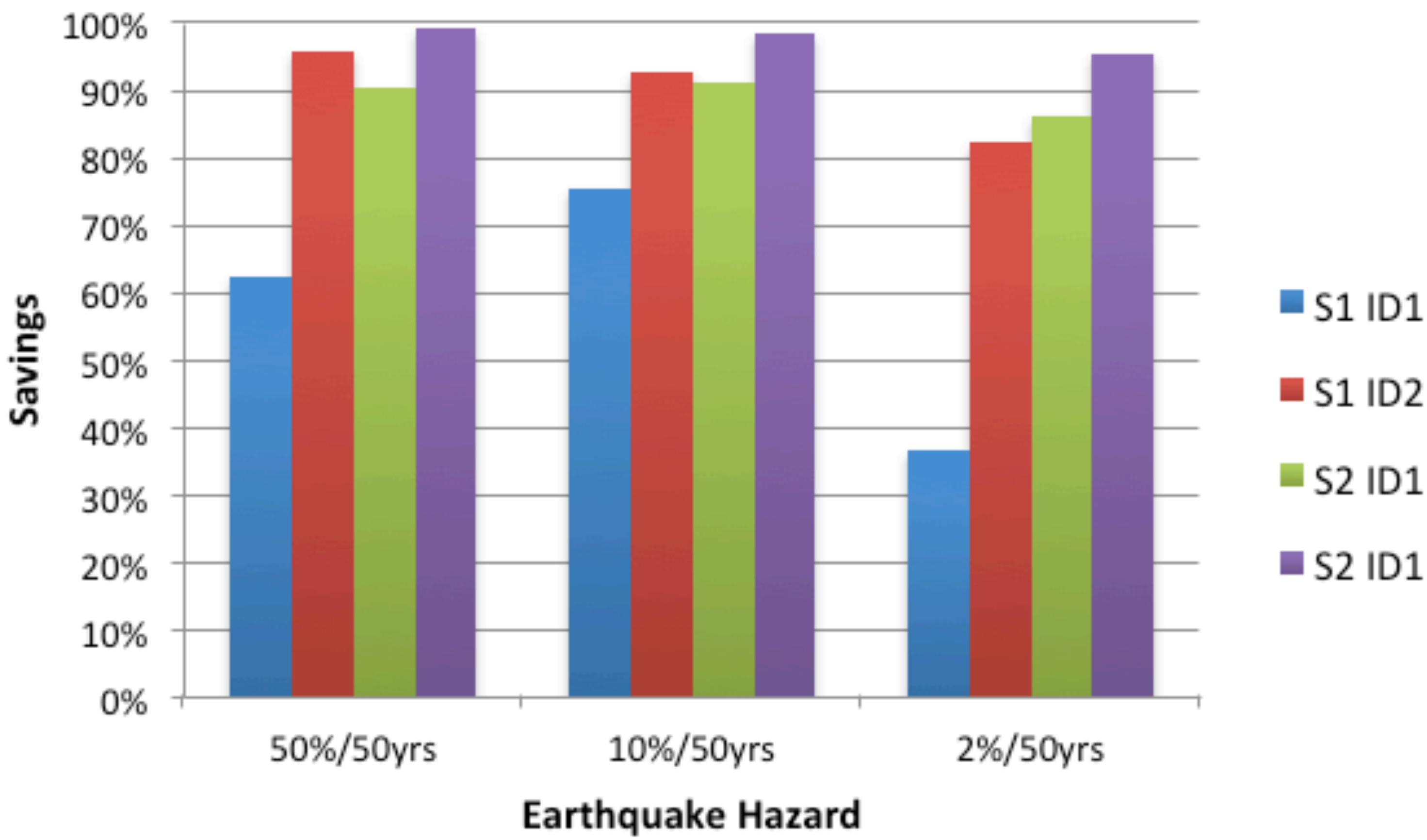


tion cost of
ice building
in downtown Oakland =
$3550/day

(LoopNet,2012)

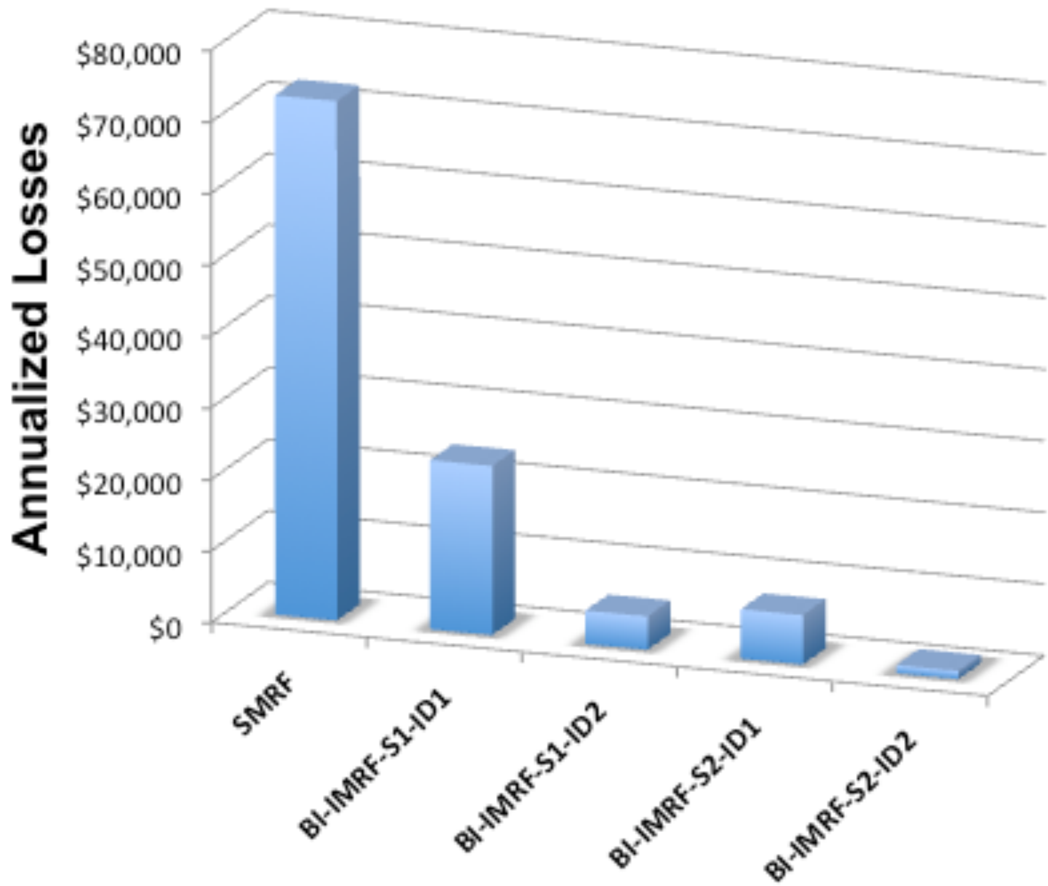
PEER

Savings of isolated systems compared to SMRF



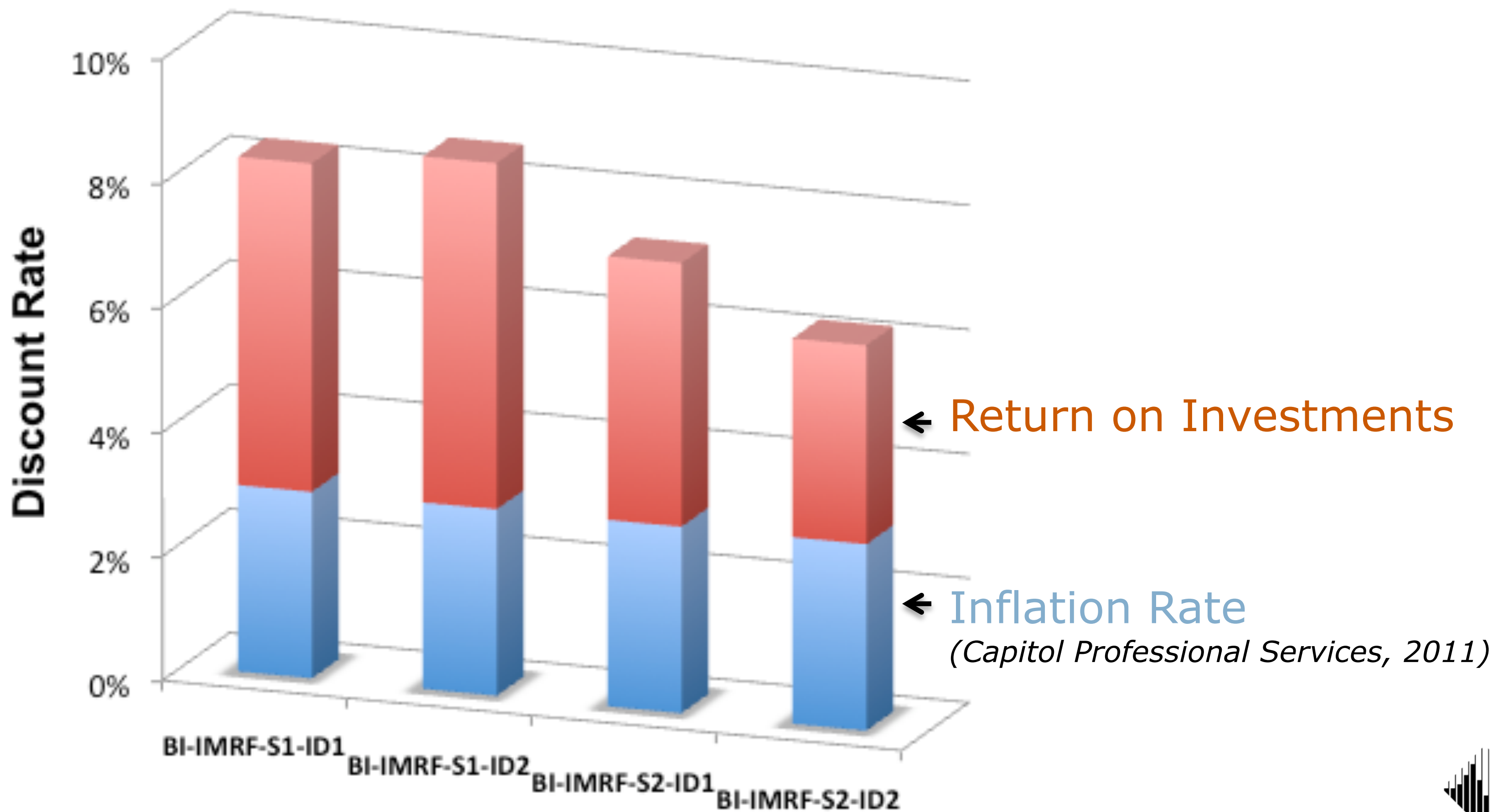
PEER

Annualized losses



PEER

Return on Investments



PEER

Conclusions

- All isolated systems have substantially smaller losses that SMRF
  - The losses can be further reduced by improving the isolation system or isolated superstructure beyond the code minimum requirements
- SMRF and baseline BI-IMRF have over a year of business downtime
- Investment in isolated systems is worthwhile; Return on Investment is ~5%
- Simple PBEE studies can help in the preliminary stages of design
  - select and proportion systems to be more resilient and robust.

PEER

Future work

- Life-cycle cost analysis of other structural system including:
  - SCBF
  - BI-OCBF
  - Viscously Damped Building
- Start from code minimum design and redesign structures to reduce business downtime and repair costs