Comparative Performance and Lifecycle Losses of Various Structural Systems

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*Building codes are **minimum** standards for public safety*

- Stated purpose:
  - "…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

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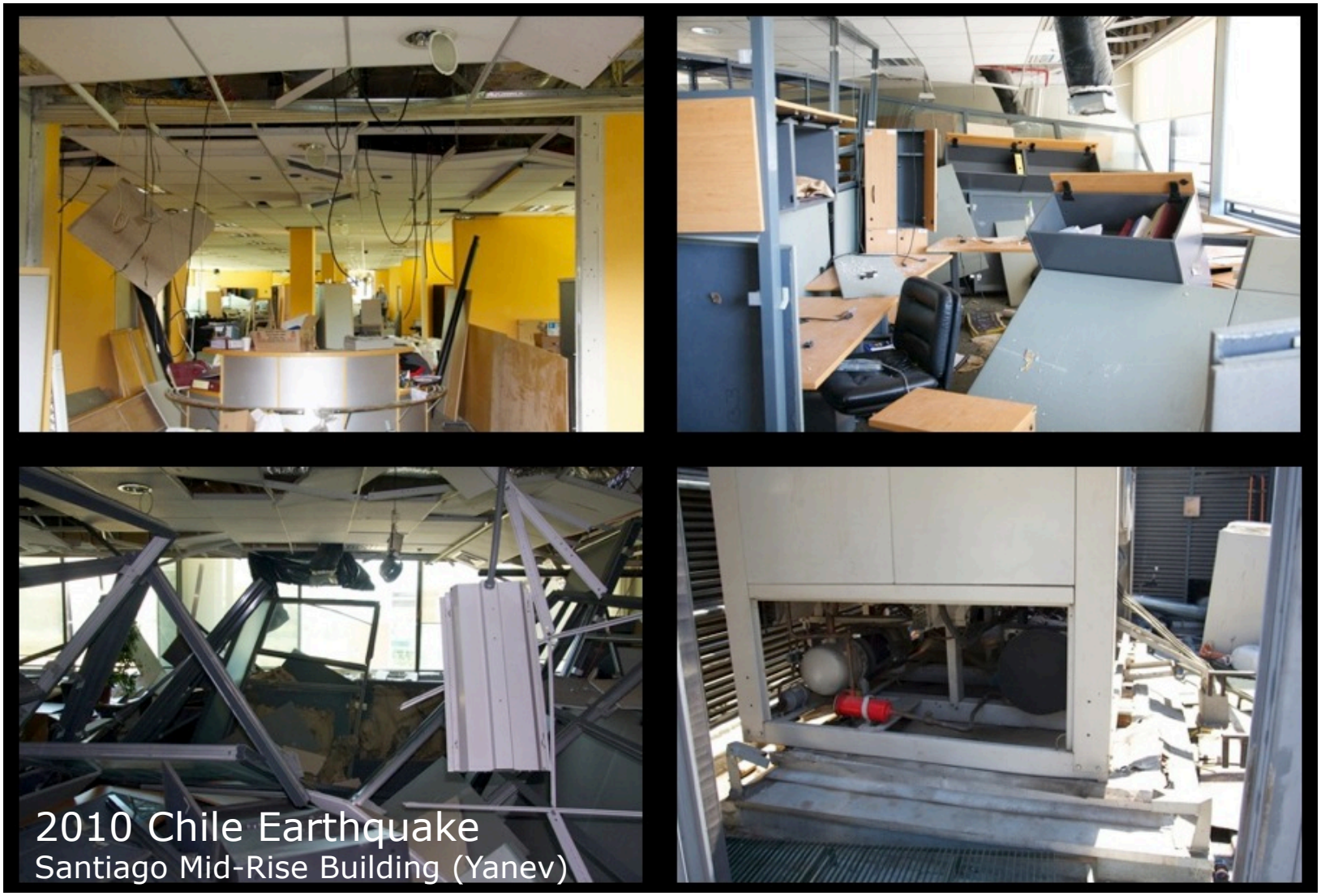
Nonstructural Elements Threaten Life Safety, and Damage is Disruptive and Expensive



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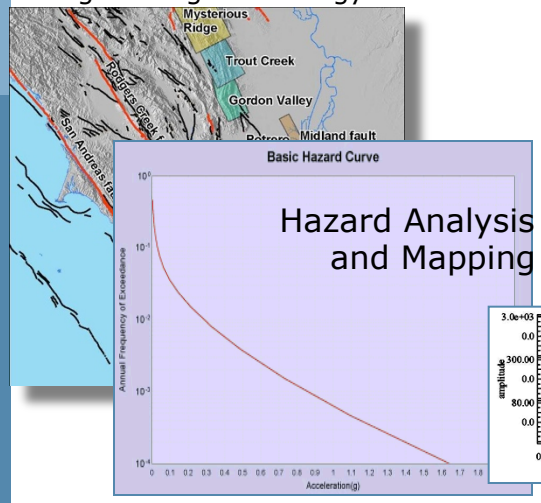
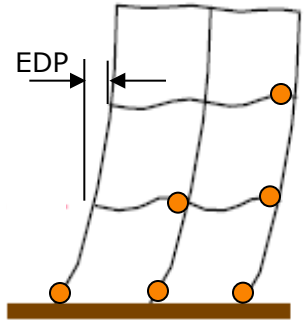
Holistic risk-oriented view:
Performance-Based Seismic Design

Engineering Seismology

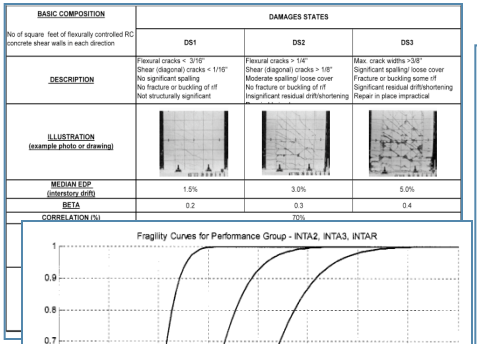


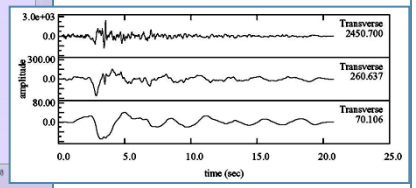
Hazard Analysis and Mapping

HPC simulation

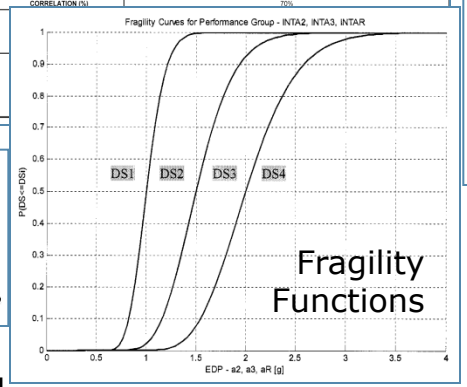


Performance Databases

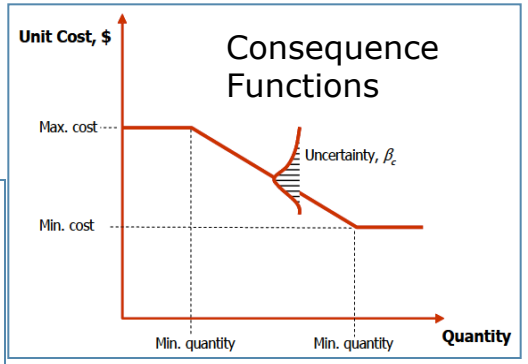




Ground motion selection and scaling



Fragility Functions



Loss Assessment

Seismic Hazard Analysis
$\lambda(im)$
IM: intensity measure

→

Response Analysis
$G(edp \mid im)$
EDP: Engineering Demand Parameter

→

Damage Analysis
$G(dm \mid edp)$
DM: Damage Measure

→

Loss Analysis
$G(dv \mid dm)$
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*

PBEE of different structural systems

- Three story steel office building
- Located in Oakland , California (~7km from Hayward fault, soil type D)
- Two lateral-load resisting systems:
  - Special Moment Resisting Frame (SMRF)
  - Base-isolated Intermediate Moment Resisting Frame (BI-IMRF)
- SMRF and BI-IMRF are designed by professional engineers based on ASCE 7 (2005) to satisfy minimum code requirements.

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Alterations of BI-IMRF

1. S1-ID1 (baseline case): Code based design
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

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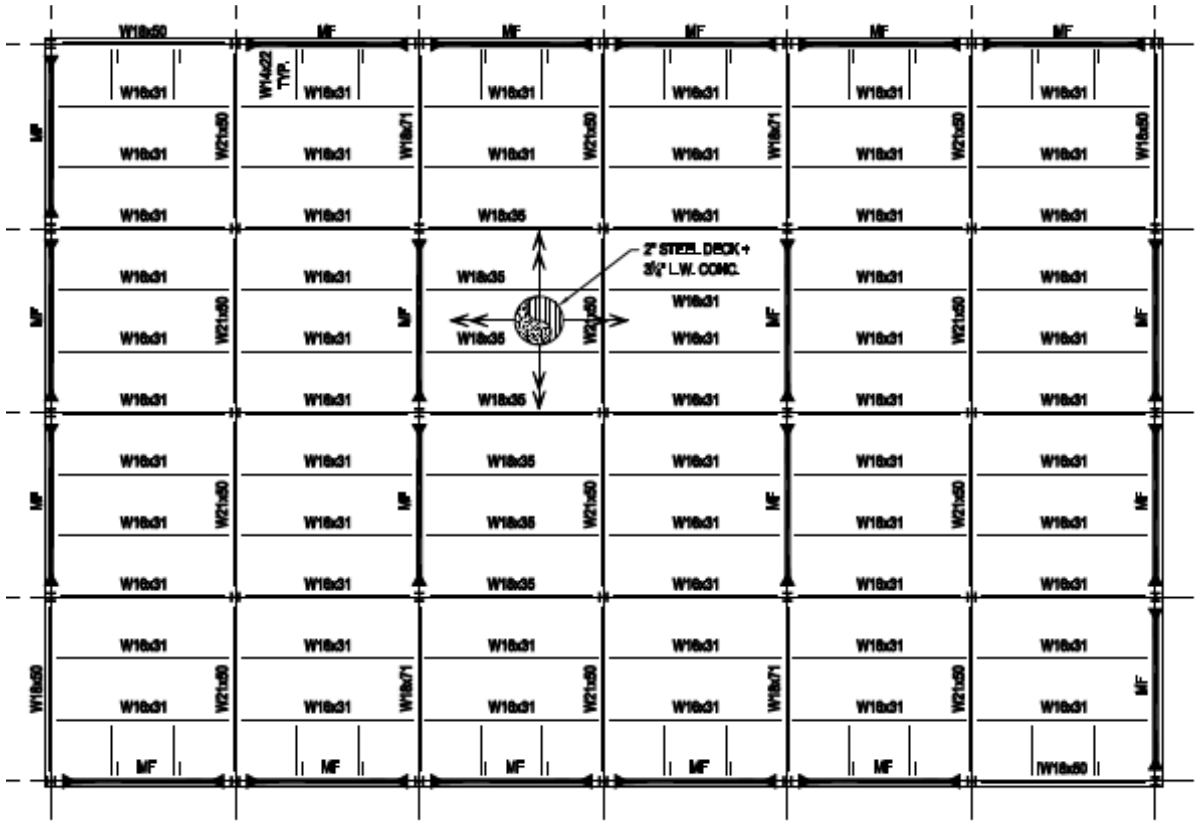
Archetype Building – Plan View



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

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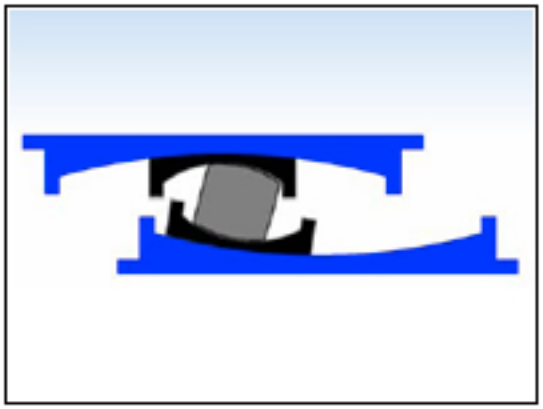
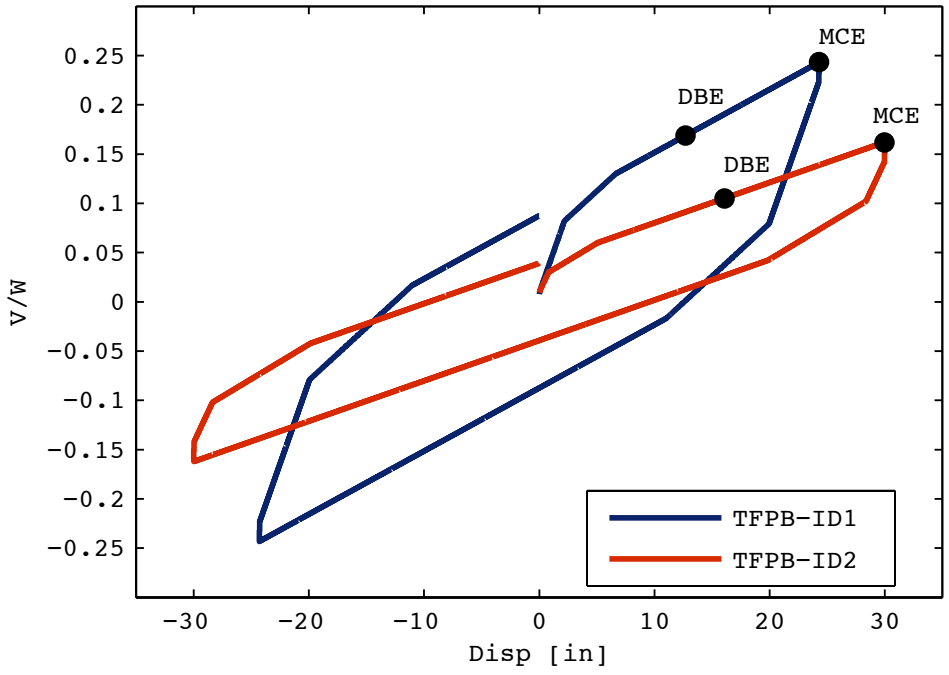
Two Design of Isolation Systems
Triple Friction Pendulum Bearings



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.



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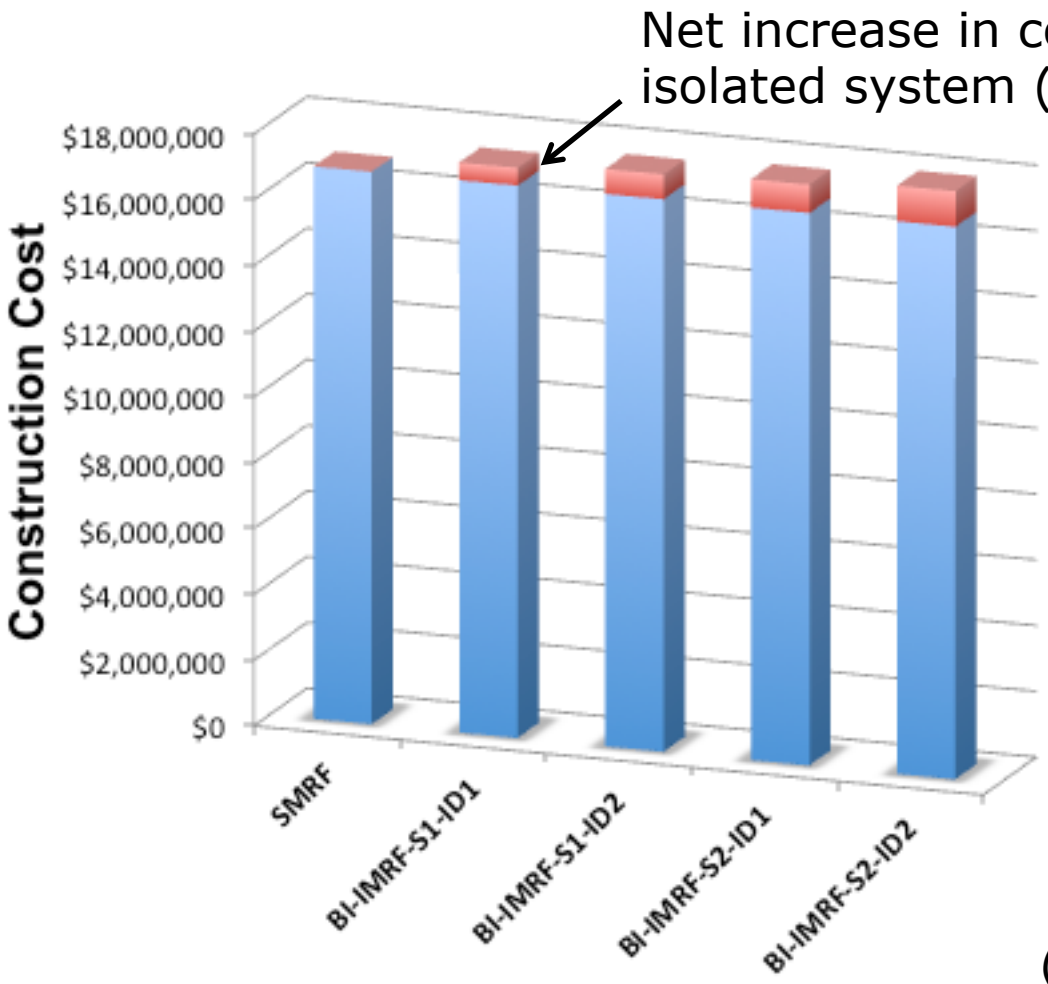
Construction Building Costs



(Ryan et al., 2010)

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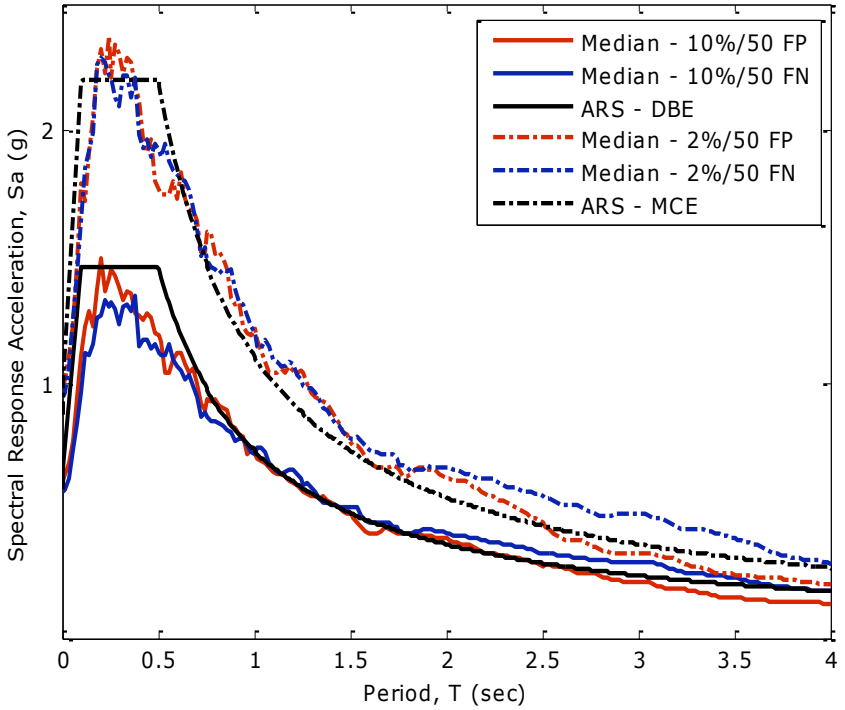
Expected ground motions at site

Based on uniform spectrum for the site, 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



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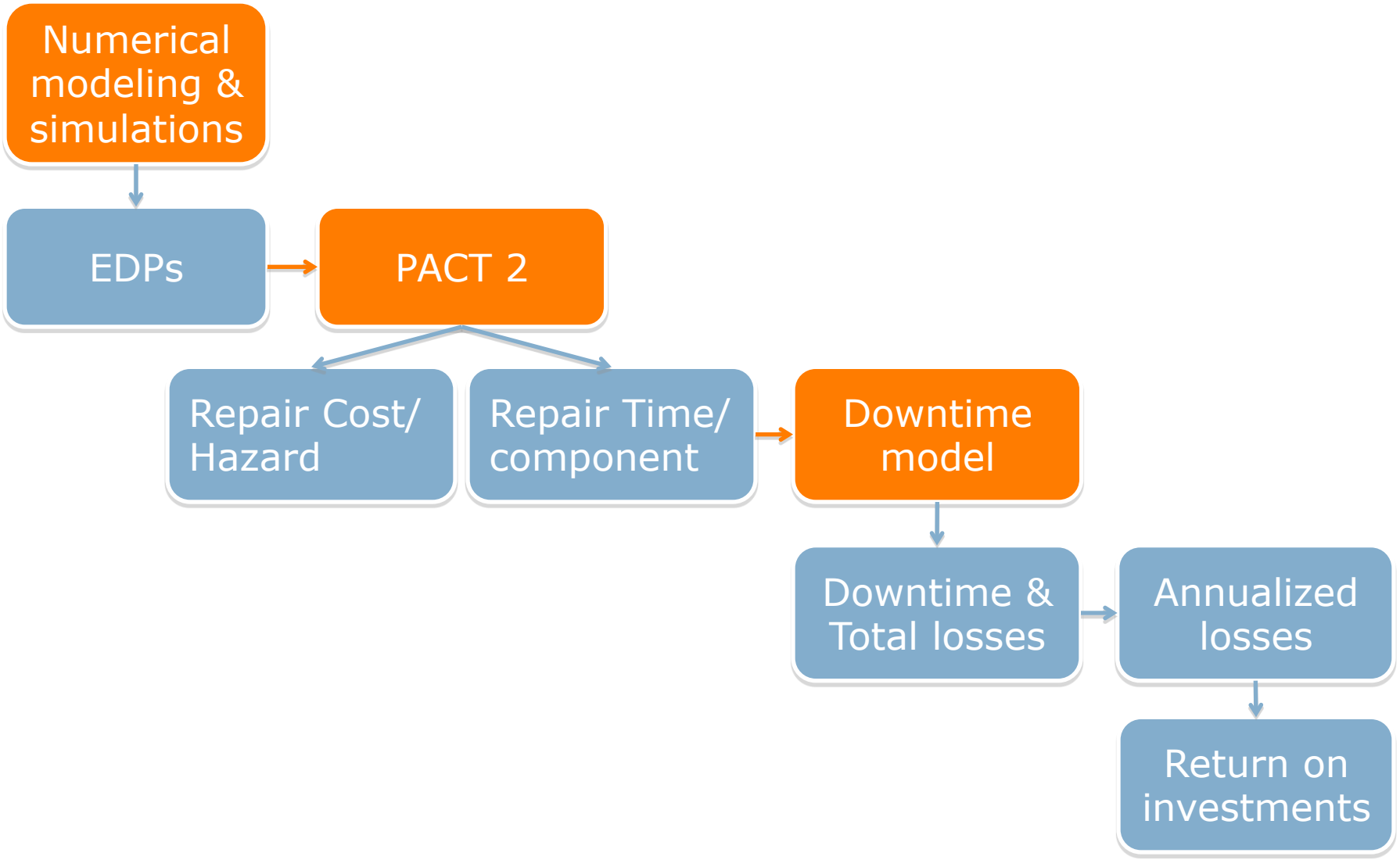
Work-flow of the analysis



Numerical Model and Methods

- Analysis performed with OpenSees
- THA performed on 2D frames
- Leaning column was modeled to account for P-Δ effects from the gravity columns
- Load – gravity & vertical and horizontal component of excitation
- Beams and columns modeled with nonlinear force-based fiber elements with low-cycle fatigue failure capabilities
- Isolators are modeled with horizontal springs and tri-linear material model assigned to it
- Geometric nonlinearity is accounted utilizing P-Δ transformation
- Damping modeled assuming damping ratio of 3%

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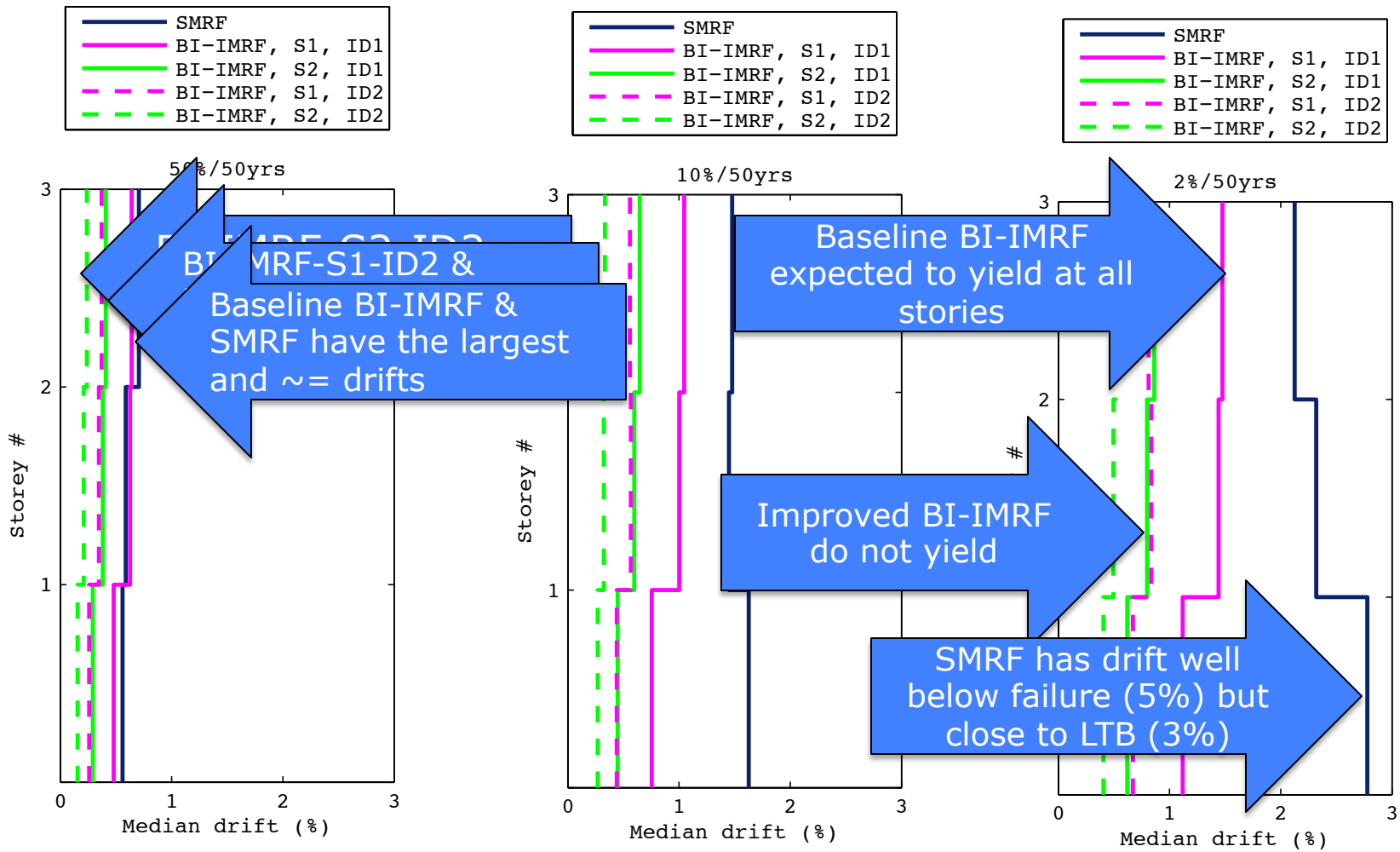
Structural Response:
Median Story Drift



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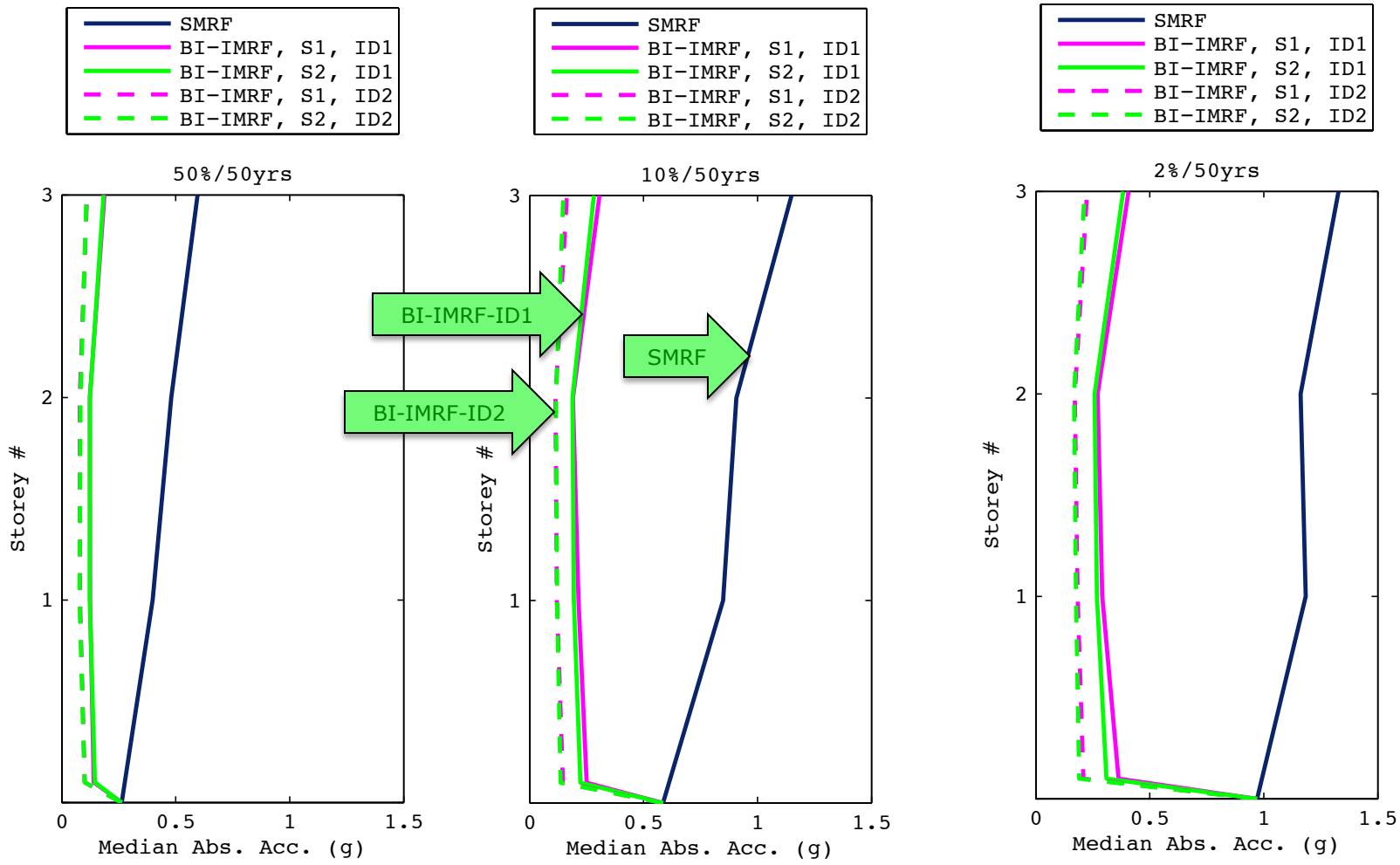
Structural Response:
Median Floor Accelerations



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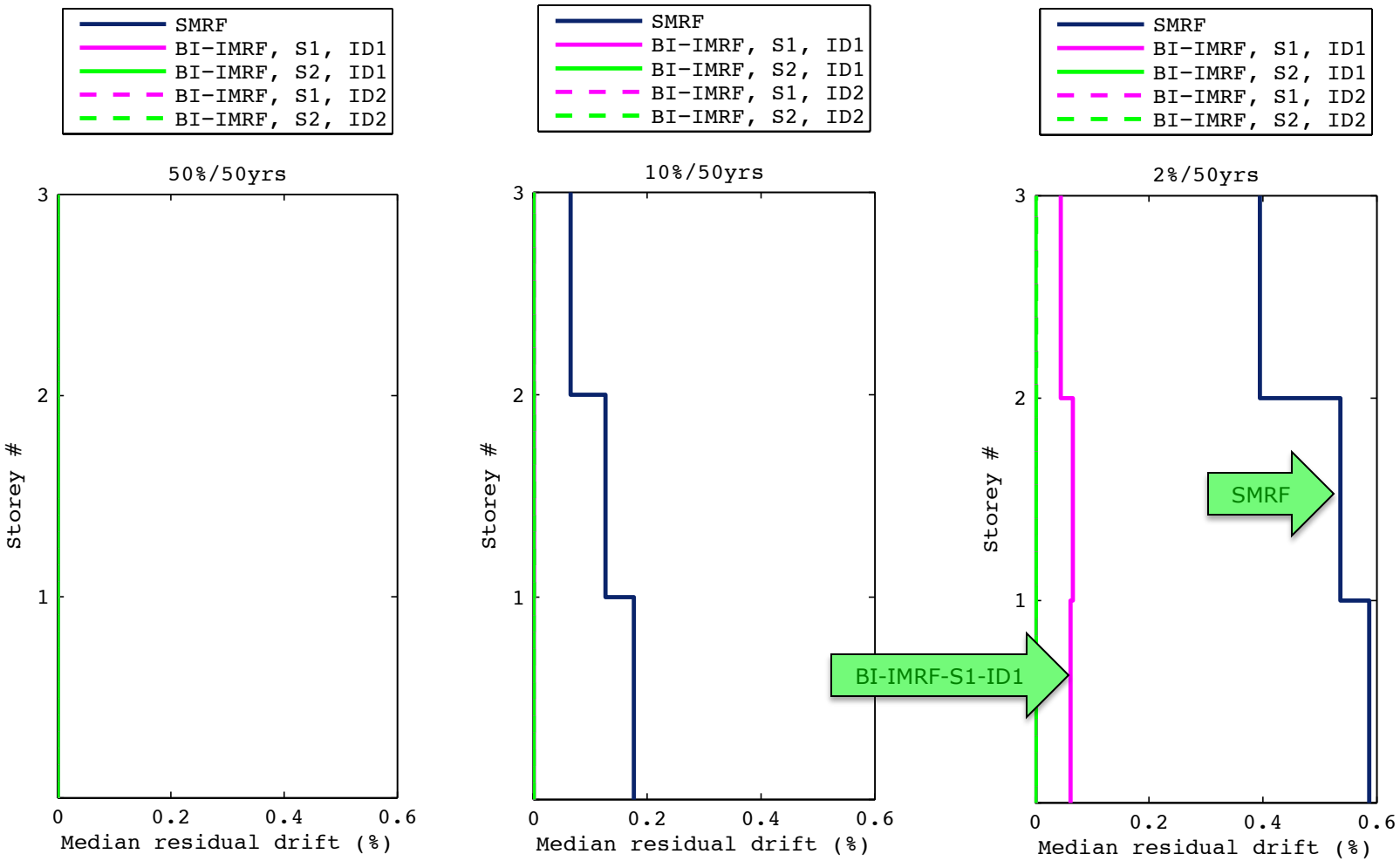
Structural Response: Residual Drifts



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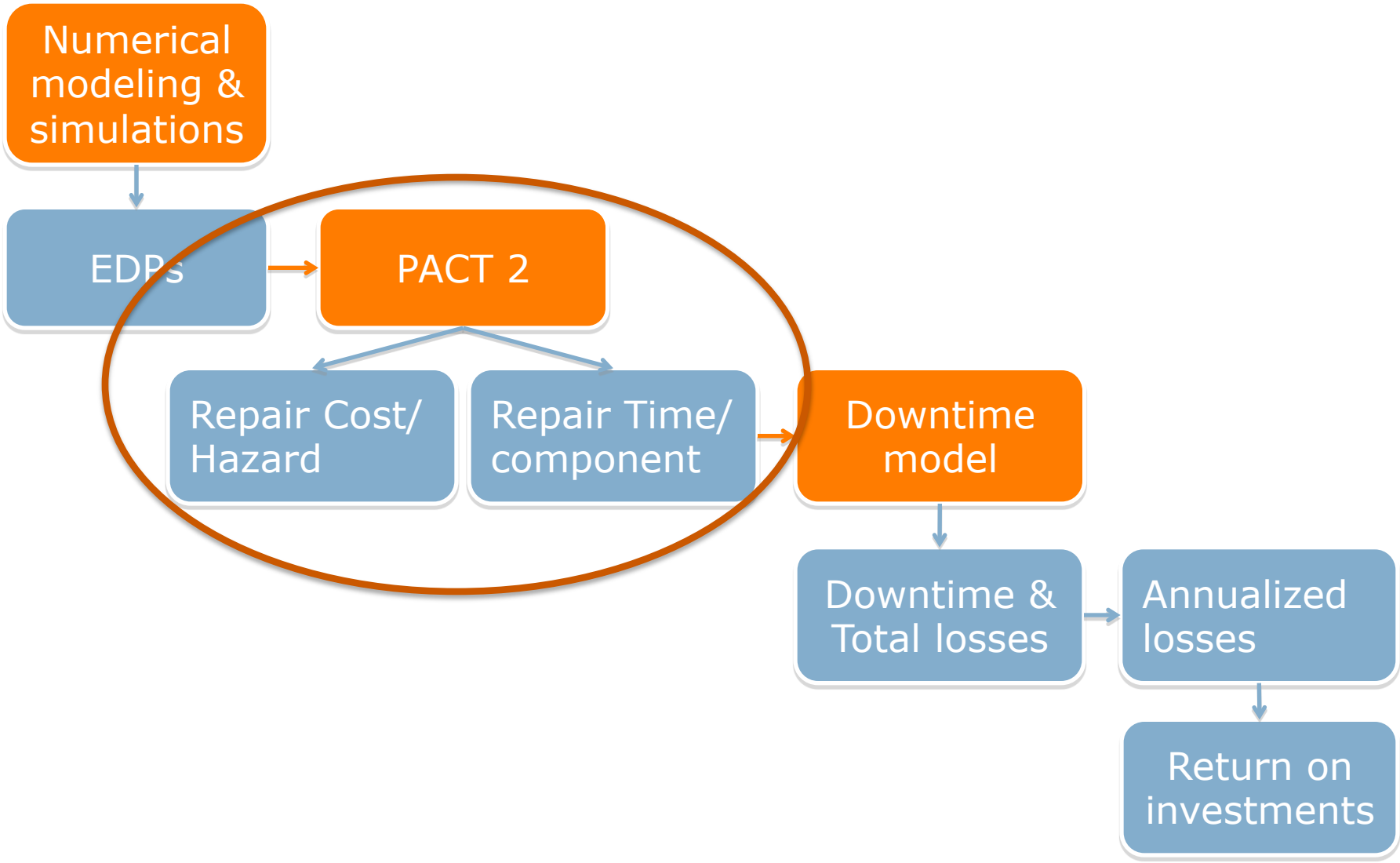
Work-flow of the analysis



PACT modeling

- Buildings information
- Define system components and their quantities

Type	Structural	Building Content	Non-structural			
Component	RBS Moment Connections (SMRF)	Desktop Electronics	Exterior Cladding	Ceiling Tiles	Fire Sprinklers	HVAC Drops
	WUF-W Moment Connections (BI-IMRF)	Bookcases	Exterior Glazing	Recessed Lighting	Chiller	Control Panel
	Welded Shear Tab Gravity Connections	Filing Cabinets	Interior Partitions	Domestic Cold Water Piping	Cooling Tower	Motor Control Center
	Column Base Plate		Pre-fabricated Steel Stairs	Domestic Hot Water Piping	Air Handling Unit	Switchgears
						Servers
	Column Splice		Traction Elevators	Sanitary Waste Piping	HVAC Ducting	Distribution Panels

- Input EDPs for each hazard level

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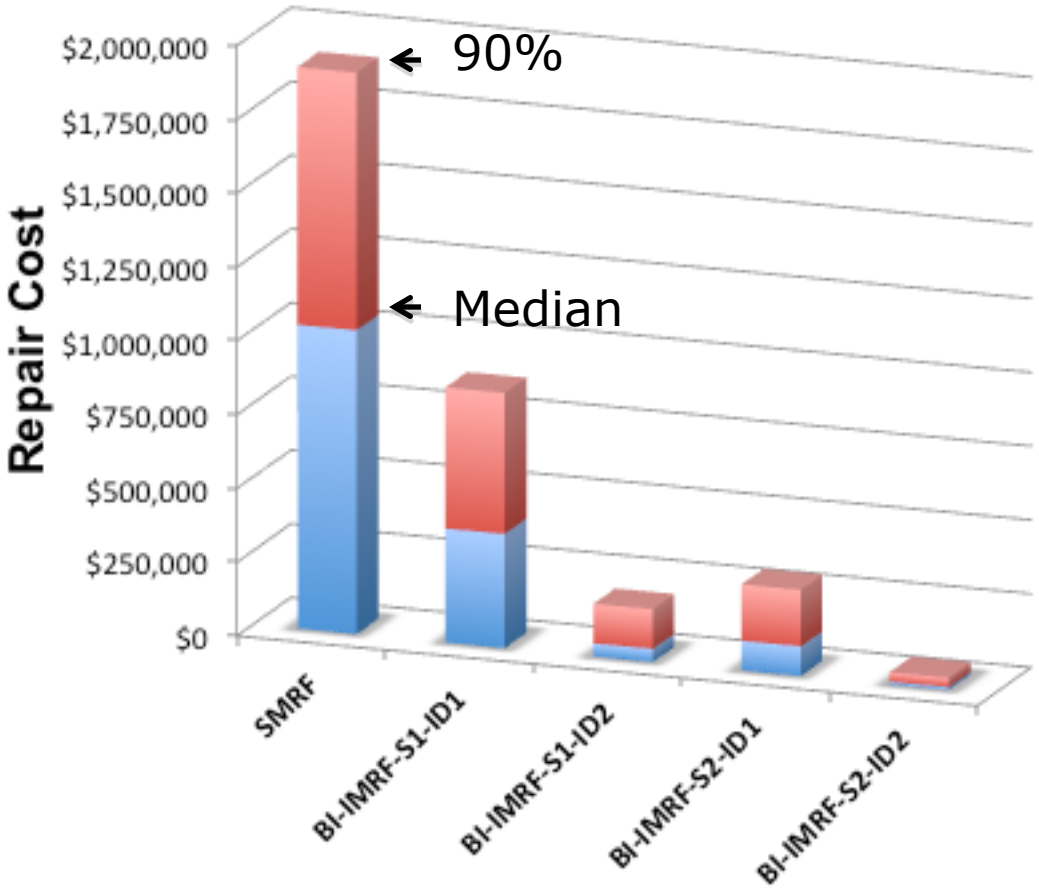
Repair Costs for scenario events:
Frequent Earthquakes (50%/50-yrs)



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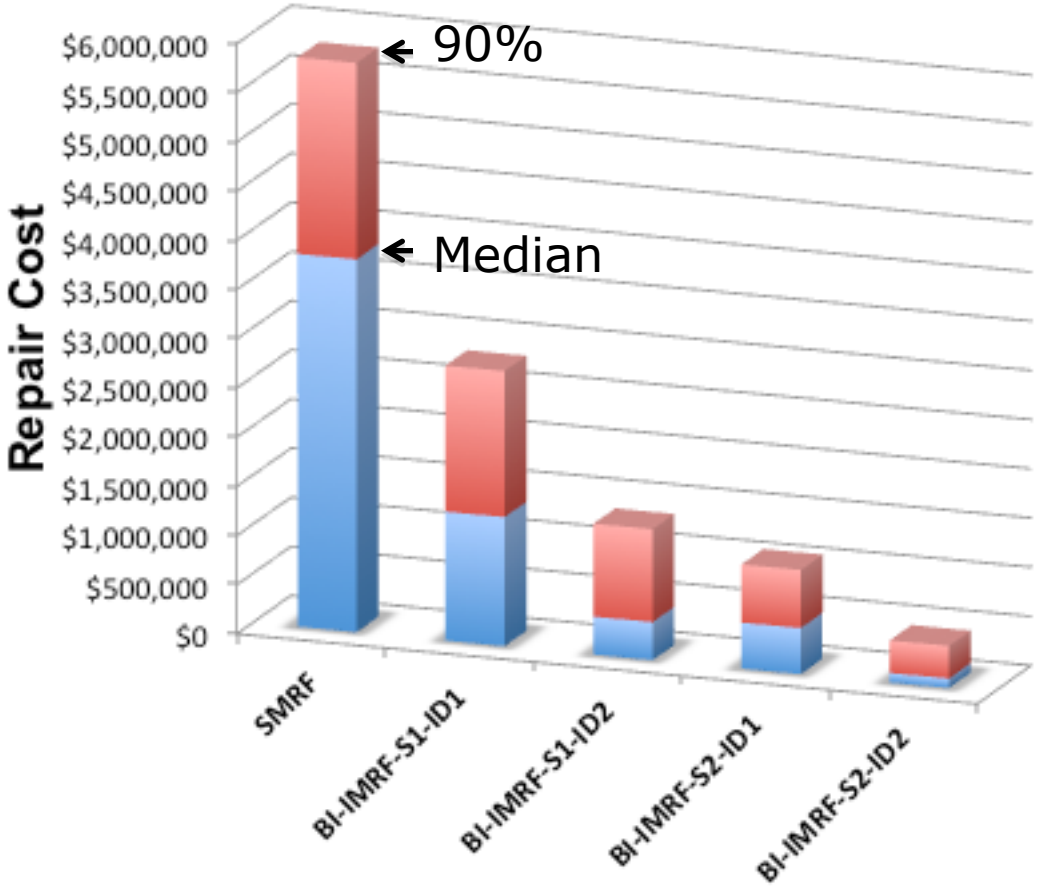
Repair Costs for scenario events:
Design Basis Earthquakes (10%/50-yrs)



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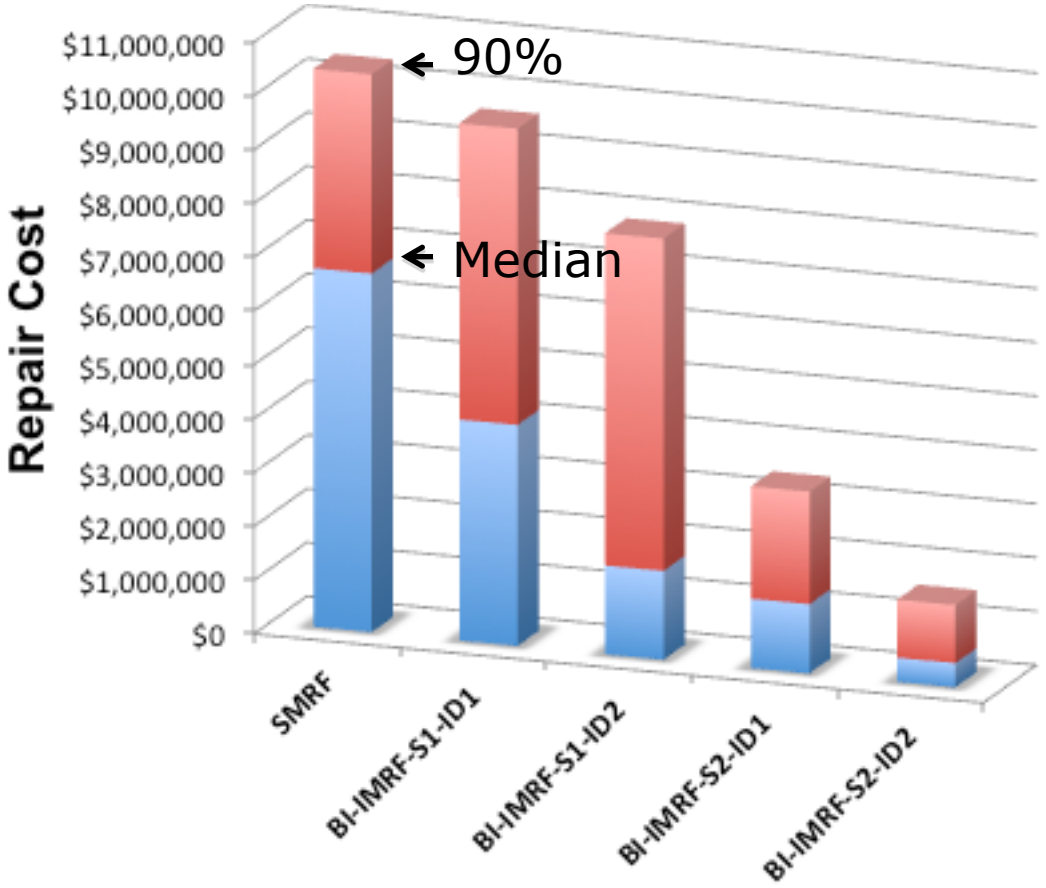
Repair Costs for scenario events:
Maximum Credible Earthquakes (2%/50-yrs)



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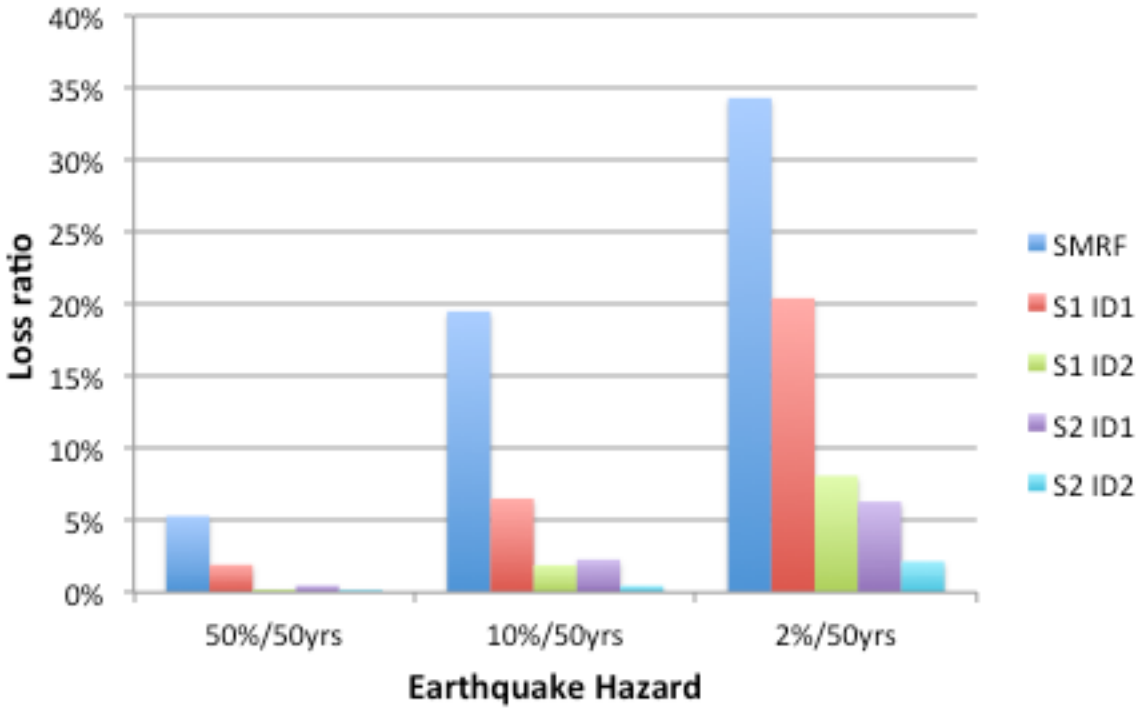
Repair Costs for scenario events:
Loss Ratio

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

Replacement Cost = 1.2 x Construction Cost



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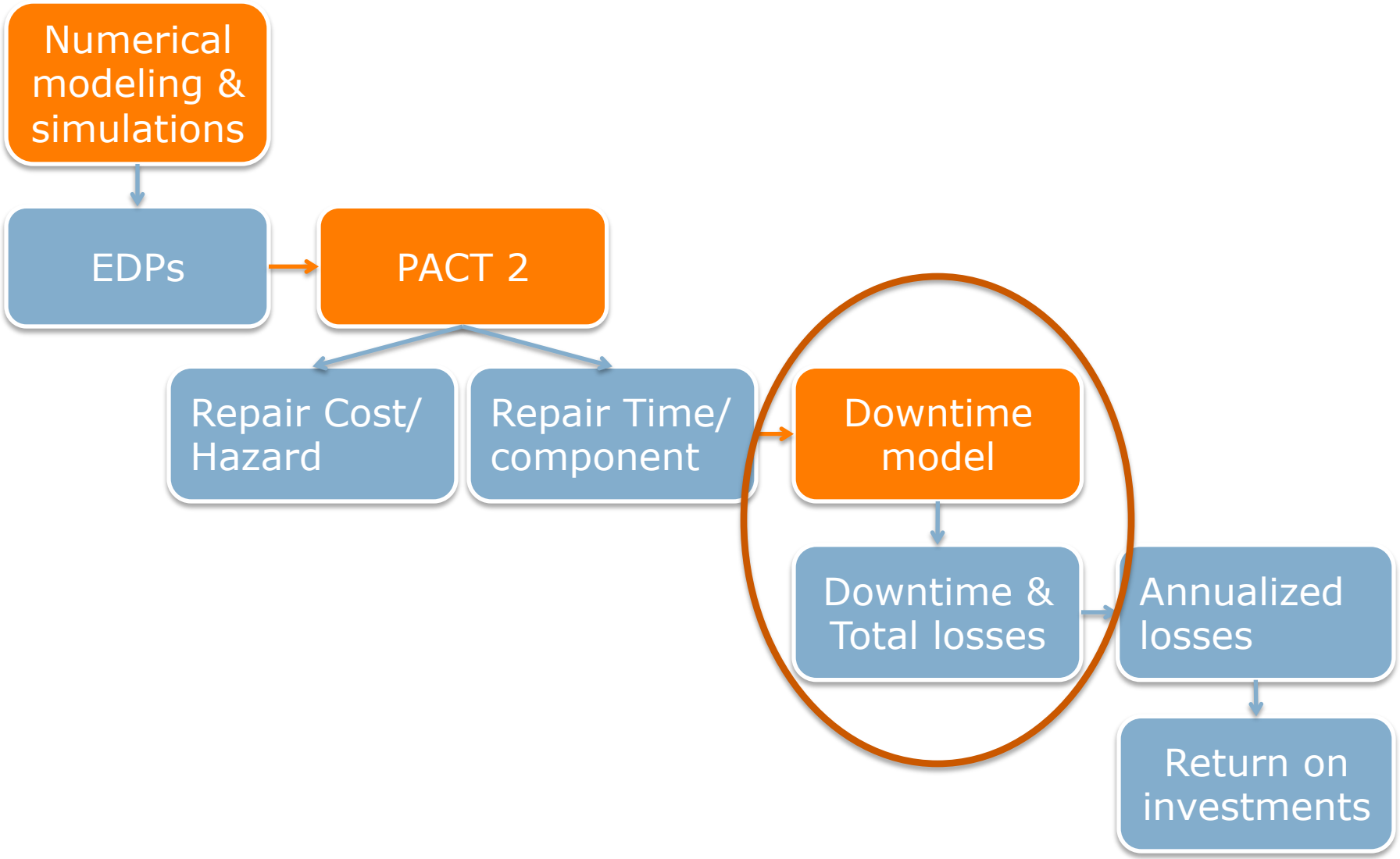
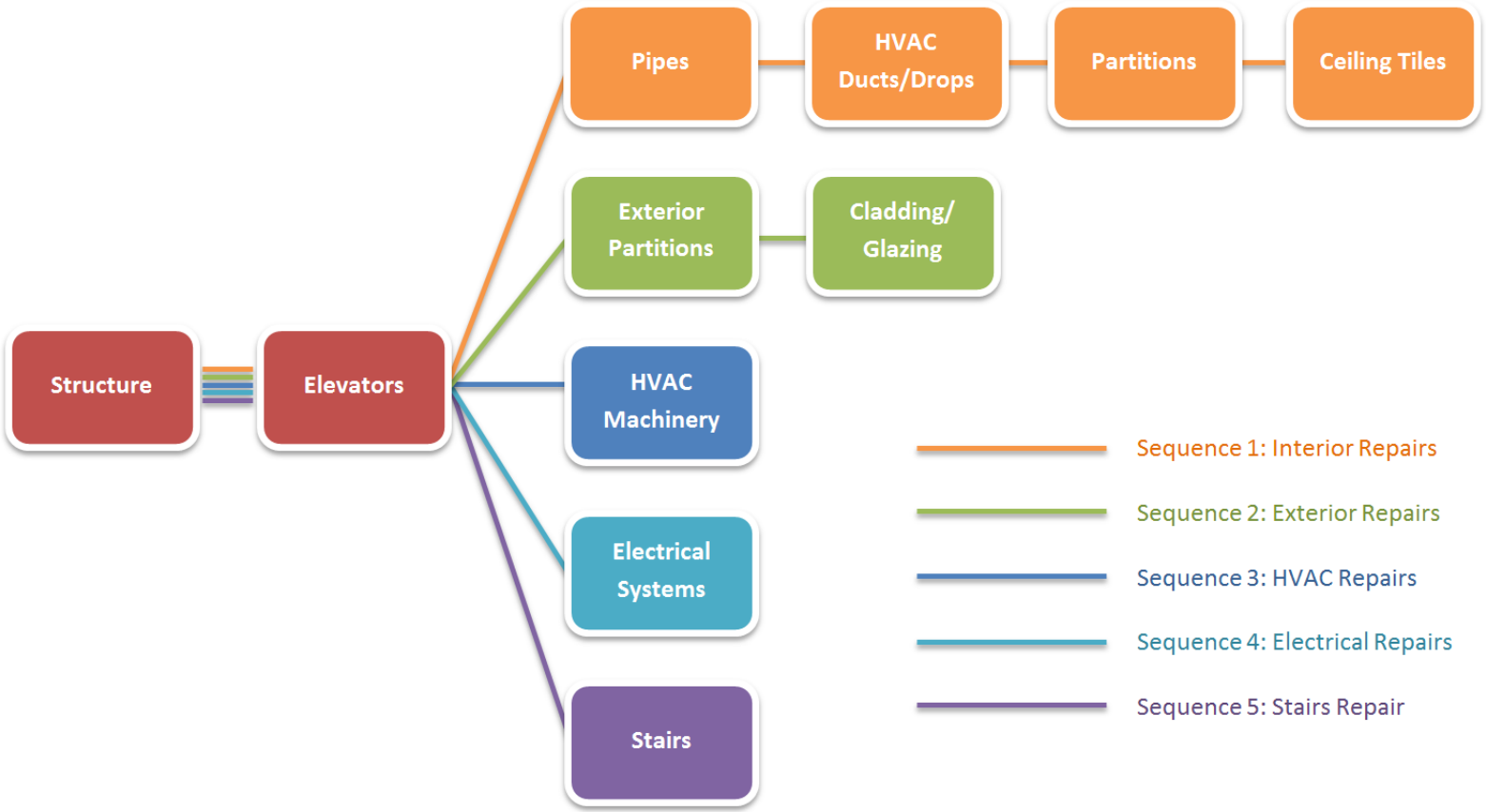
Work-flow of the loss analysis



Business downtime:
Repair time for functional recovery



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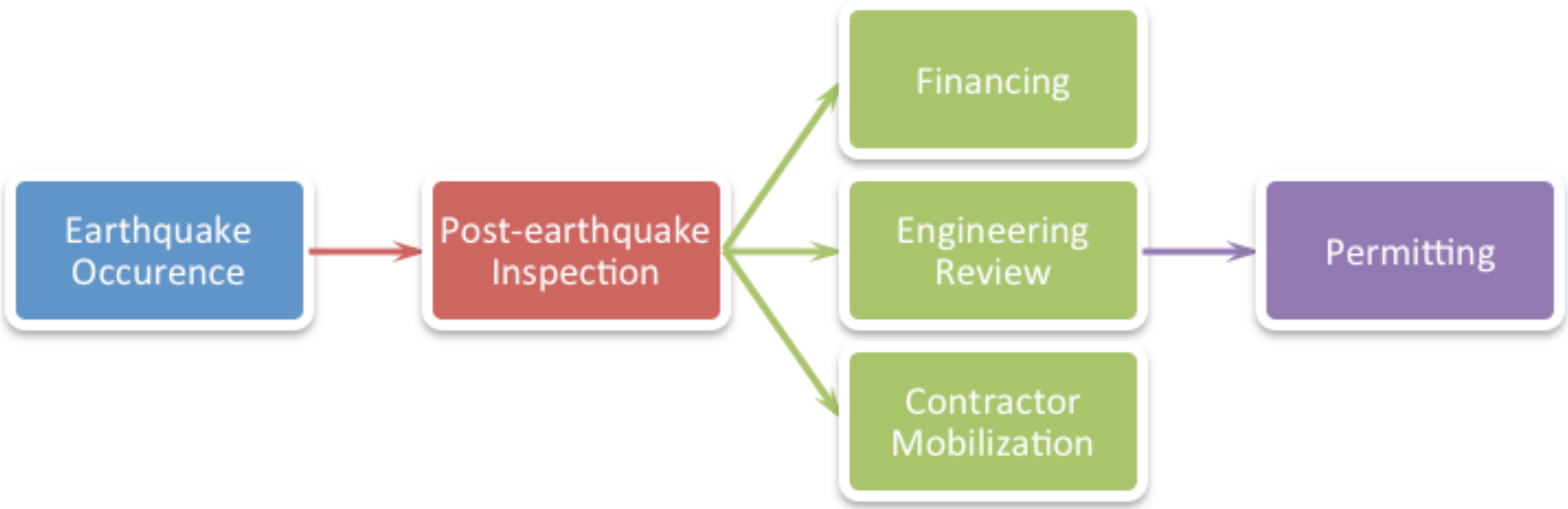
Business Downtime:
Mobilization Time



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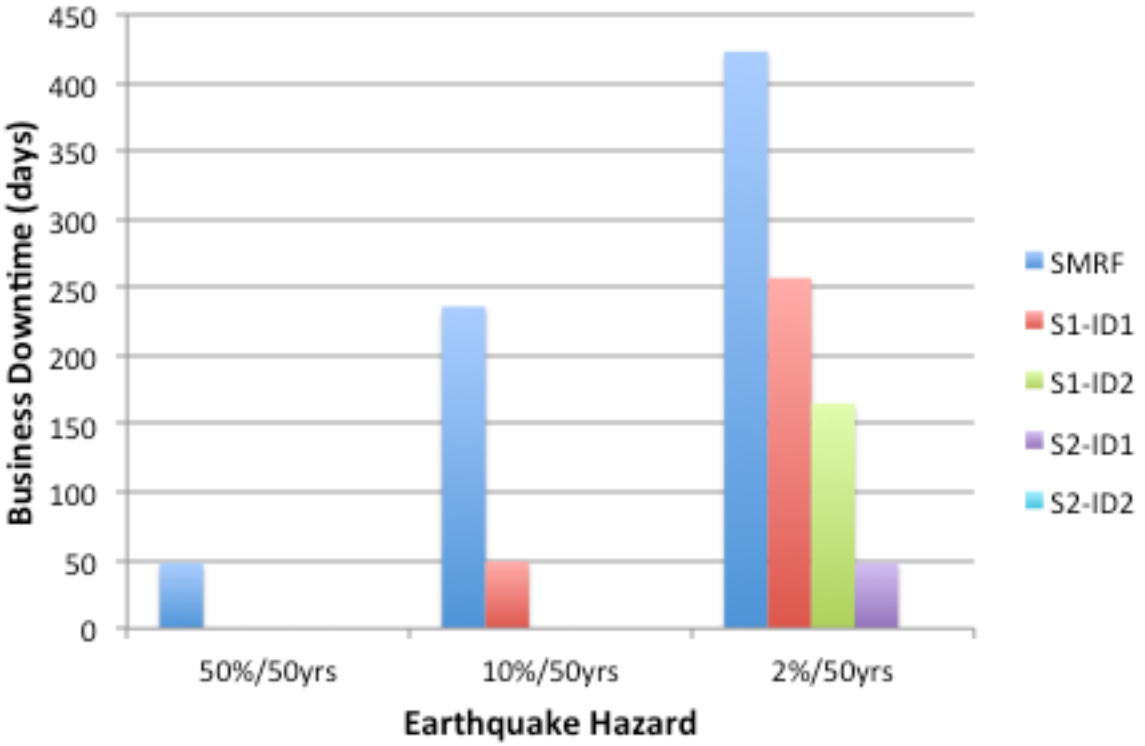
Business Downtime



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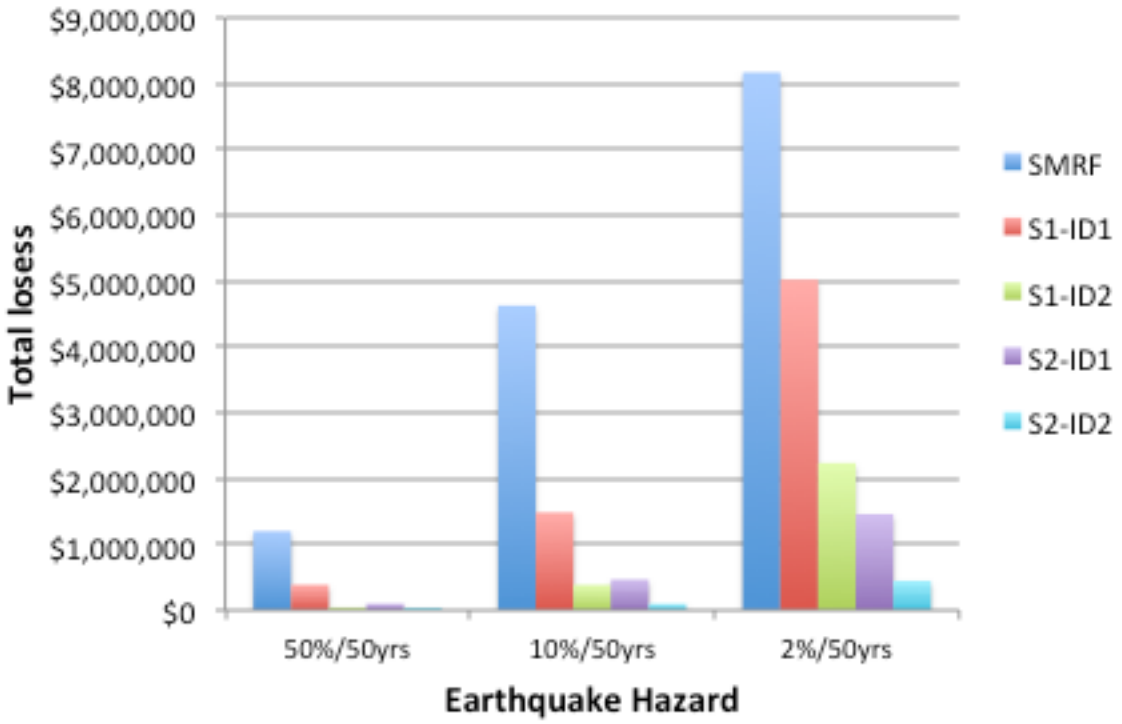
Total Losses = Repair + Business Interruption

Business interruption cost of a three storey office building in downtown Oakland = $3550/day

(LoopNet,2012)



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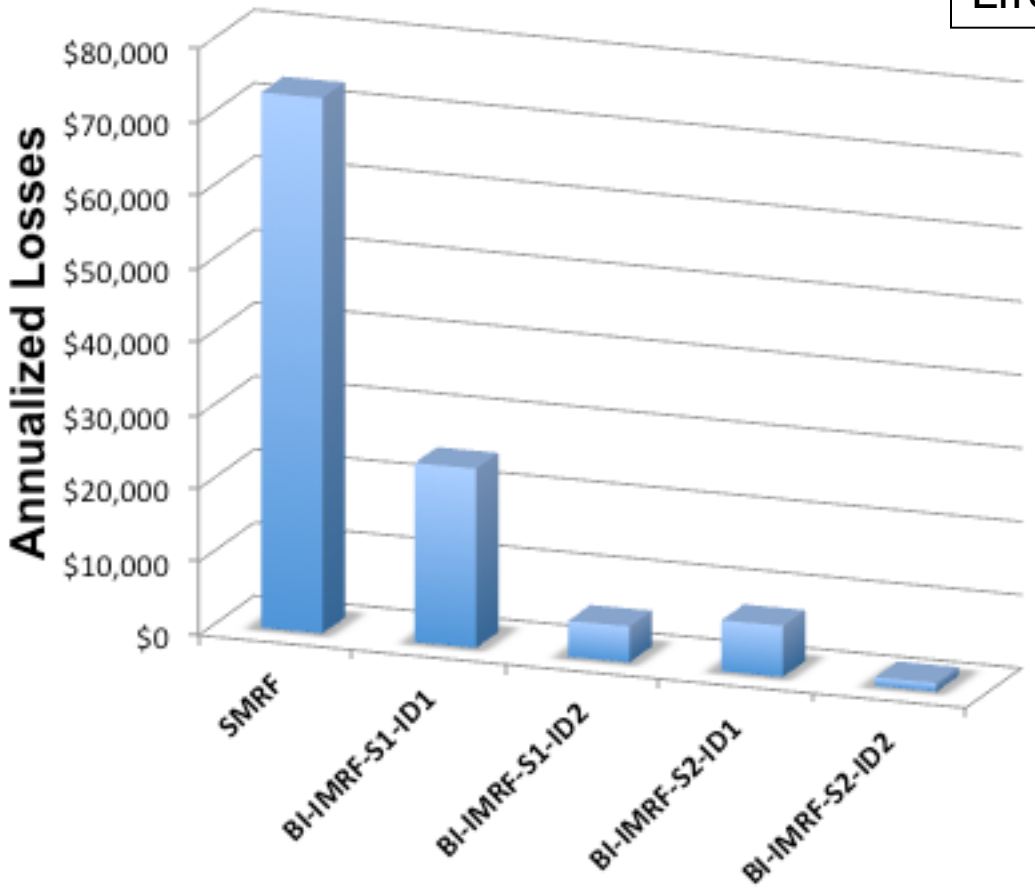
Annualized losses

Life cycle = 50 years



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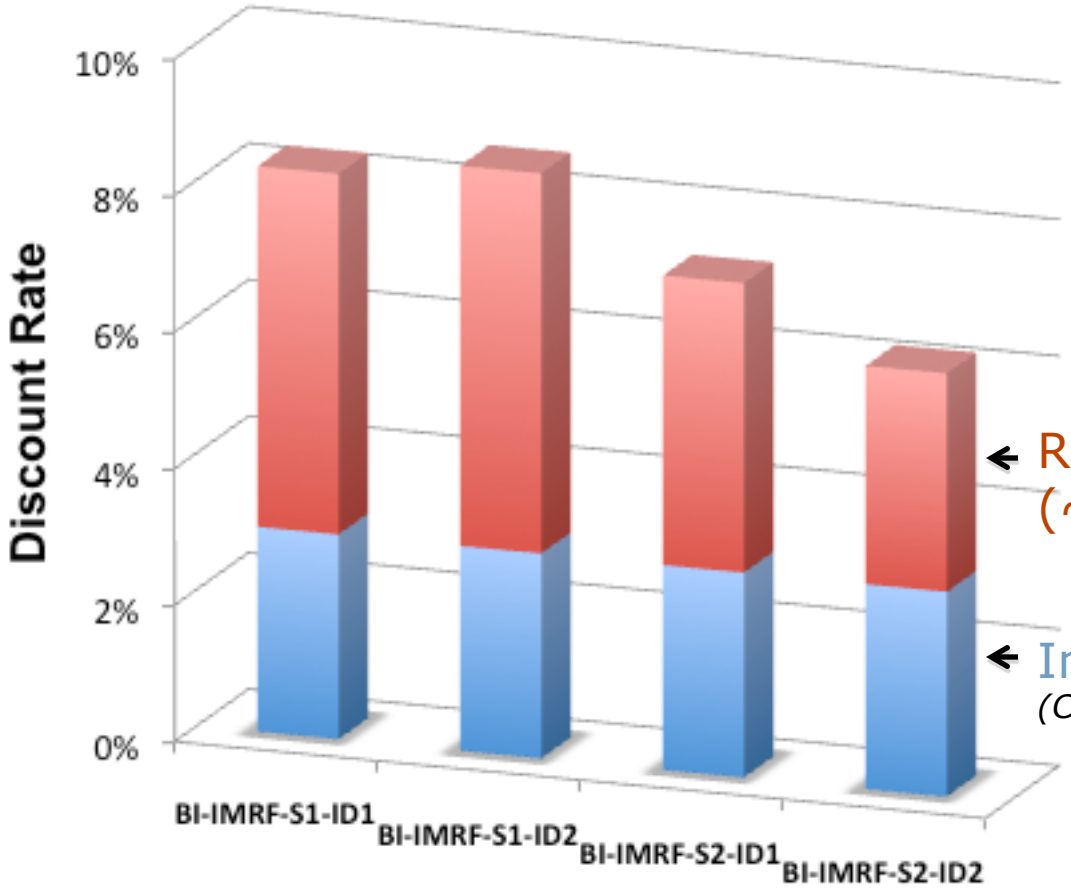
Return on Investments



← Return on Investments (~5%)

← Inflation Rate

(Capitol Professional Services, 2011)

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Conclusions

- PBEE studies can help in the preliminary stages of design
  - select and proportion systems to be more resilient and robust.
- All isolated systems have substantially smaller losses that fixed-base system
  - The losses were further reduced by improving the isolation system or isolated superstructure beyond the code minimum requirements
- Isolated system with improved both isolation system and superstructure provide continued functionality at all hazard levels
- Investment in isolated systems is worthwhile; Minimum Return on Investment is ~5%

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Future work

- Life-cycle cost analysis of other structural system including:
  - SCBF
  - BI-OCBF
  - Viscously Damped Building
- Improve loss estimation to account for residual drifts in the loss analysis
- Develop broad set of business models

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Acknowledgments

- PEER for its support
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- Victor Zayas
- ARUP

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Questions?