Life-Cycle Cost and Performance Comparisons of Different Code-Complaint 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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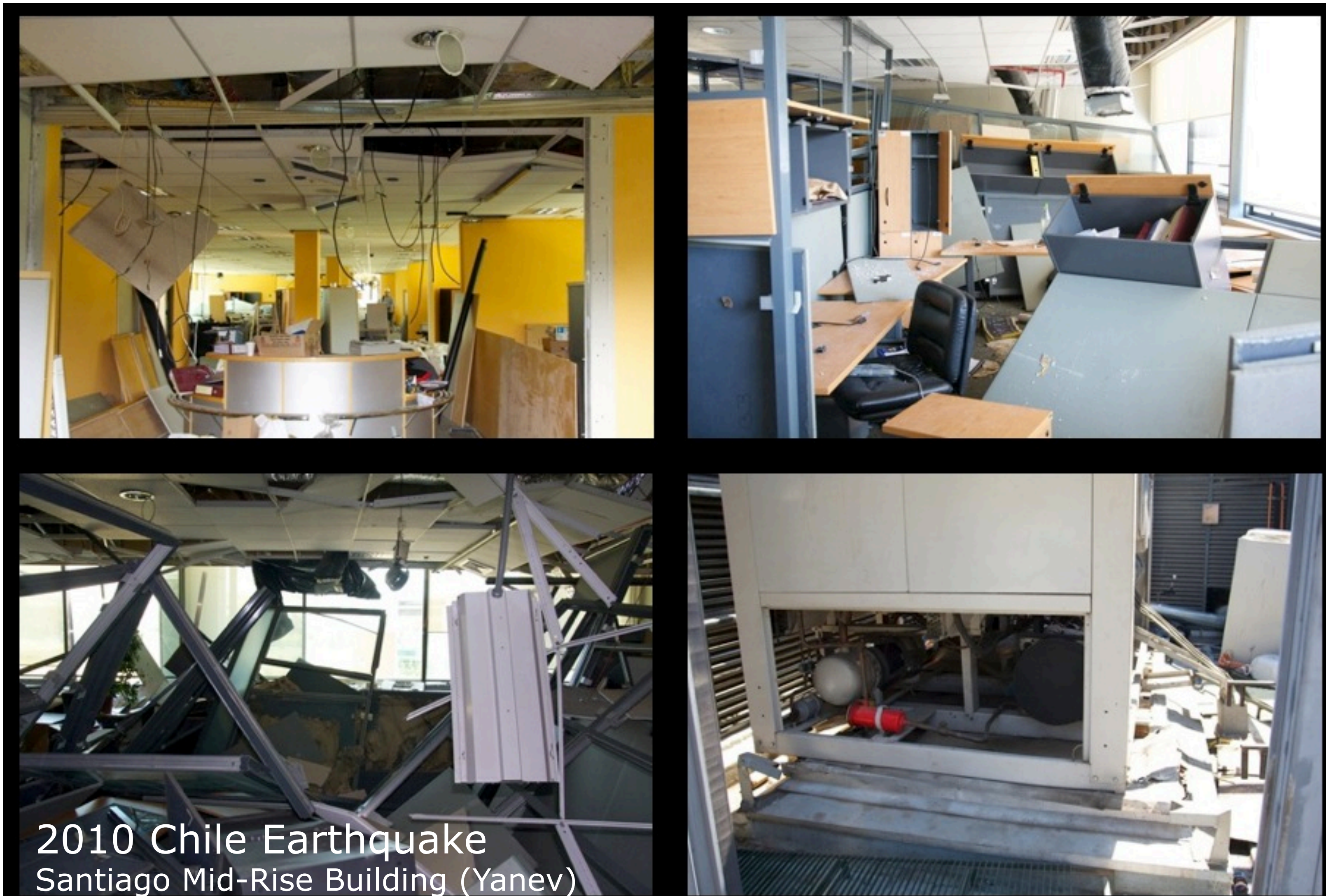
Nonstructural Elements Threaten Life Safety, and Damage is Disruptive and Expensive



2010 Chile Earthquake
Santiago Mid-Rise Building (Yanev)

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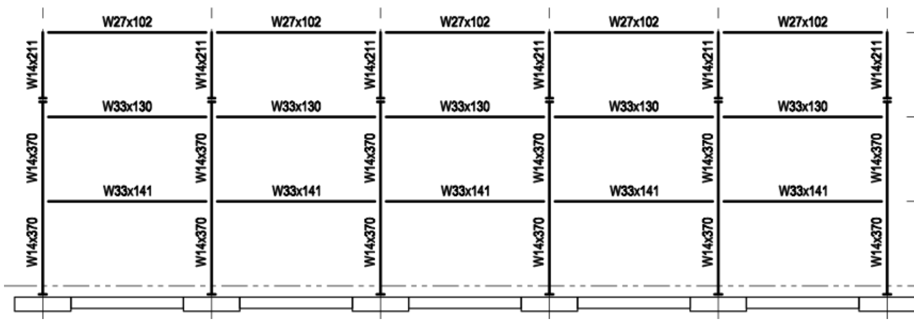
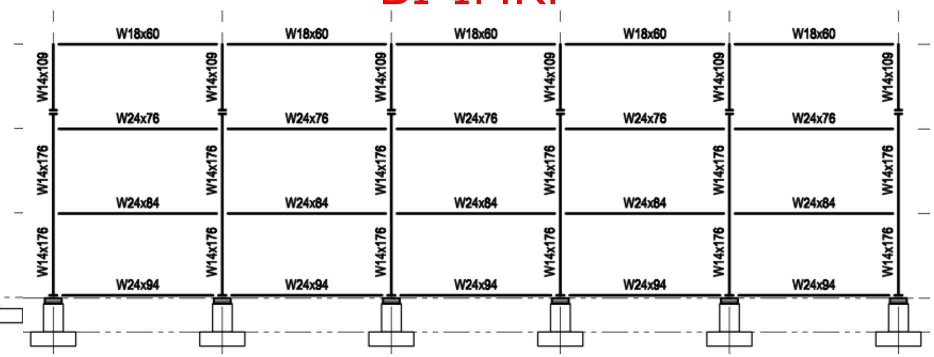
PBEE used to estimate losses of various code compliant systems

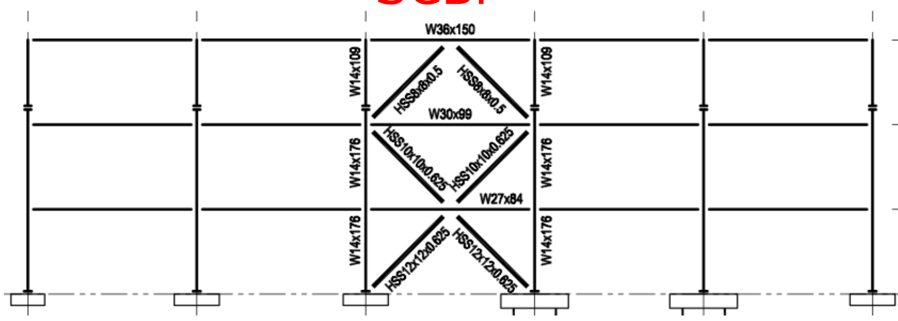
SMRF



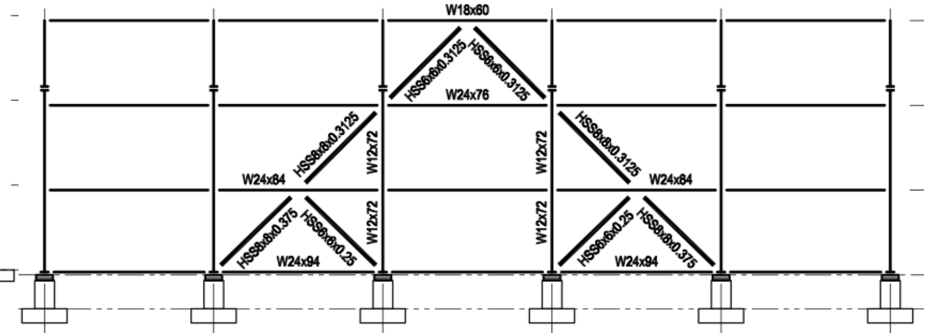
BI-IMRF



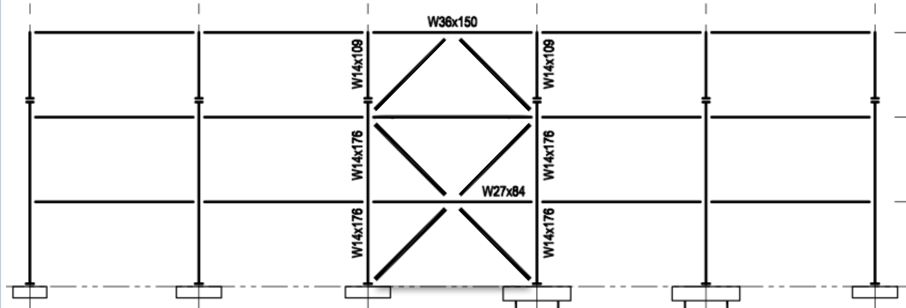
SCBF



BI-OCBF



BRBF



VDMF

PBEE used to estimate losses of various code compliant systems

- Performance, annualized losses, and return on investments are compared
- Occupancy type: office building
- The building owner rents the space
- Life-cycle cost analysis performed considering 3 hazard levels (50%/50yrs, 10%/50yrs, 2%/50yrs)
- Life-cycle cost analysis was based on:
  - Initial construction cost
  - Expected repair cost
  - Minimum monetary loss due to business interruption

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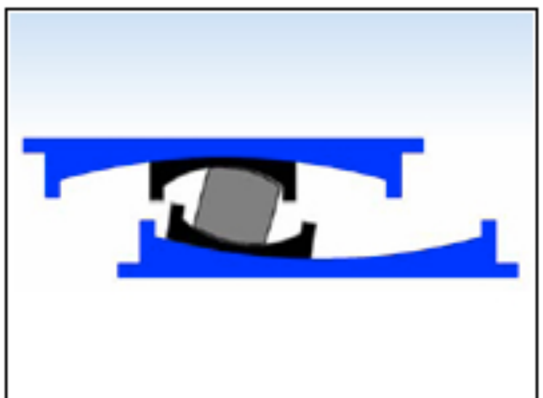
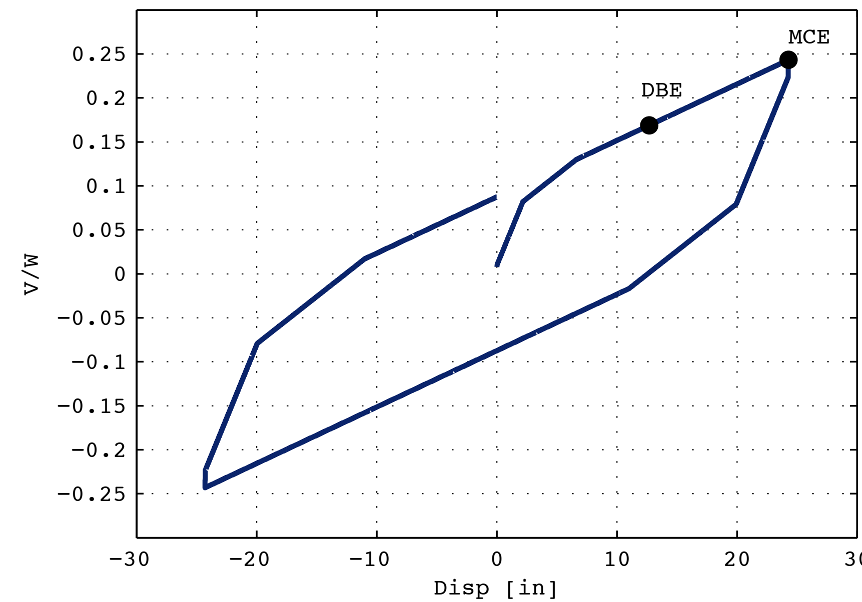
Isolation Systems
Triple Friction Pendulum Bearings



Isolator Properties	DBE	MCE
Effective period	2.77 sec	3.07 sec
Effective damping	24.2 %	15.8 %
Isolator displacement	12.7 in.	24.3in.



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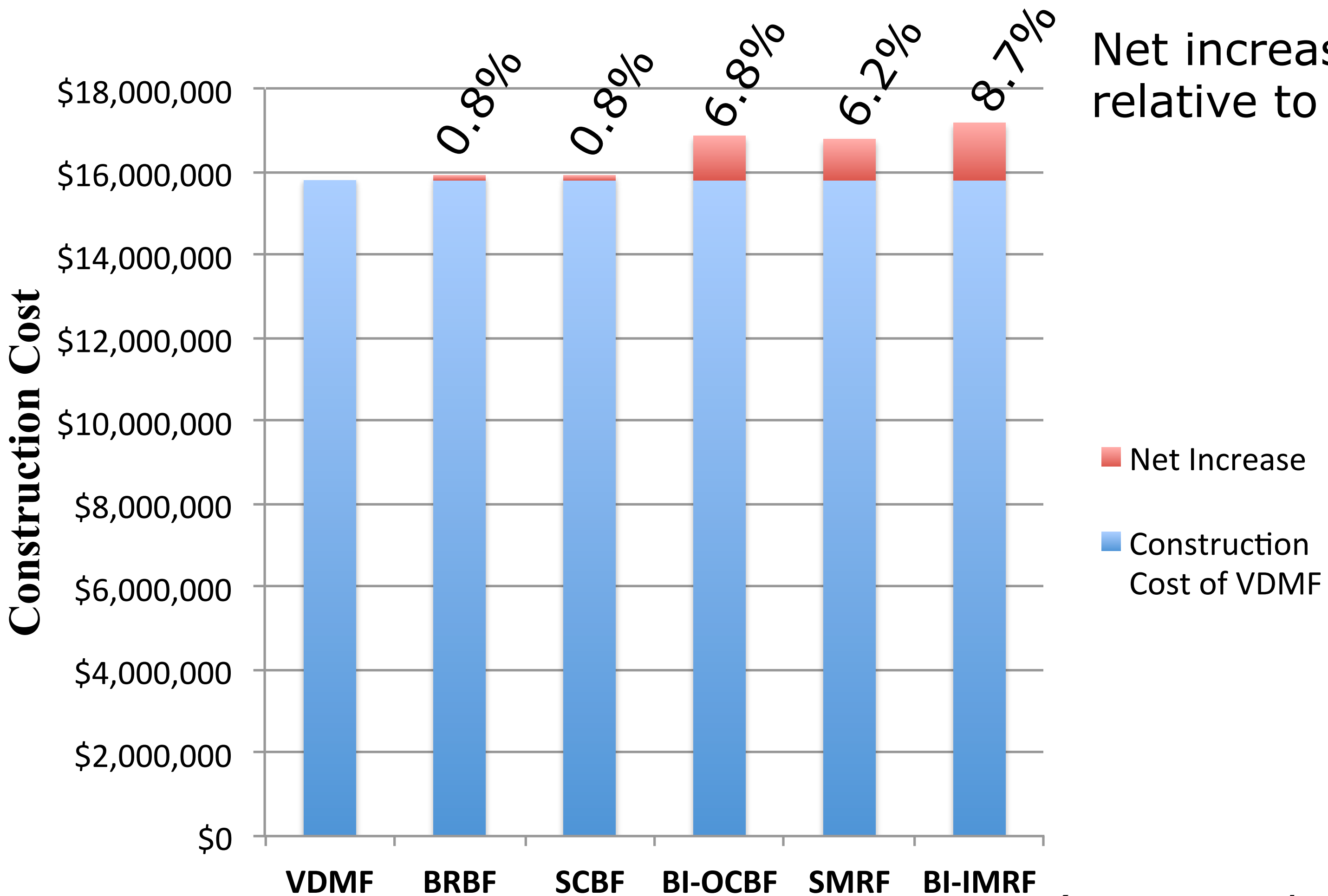
Construction Building Costs



Net increase in cost relative to VDMF

(Ryan et al., 2010)

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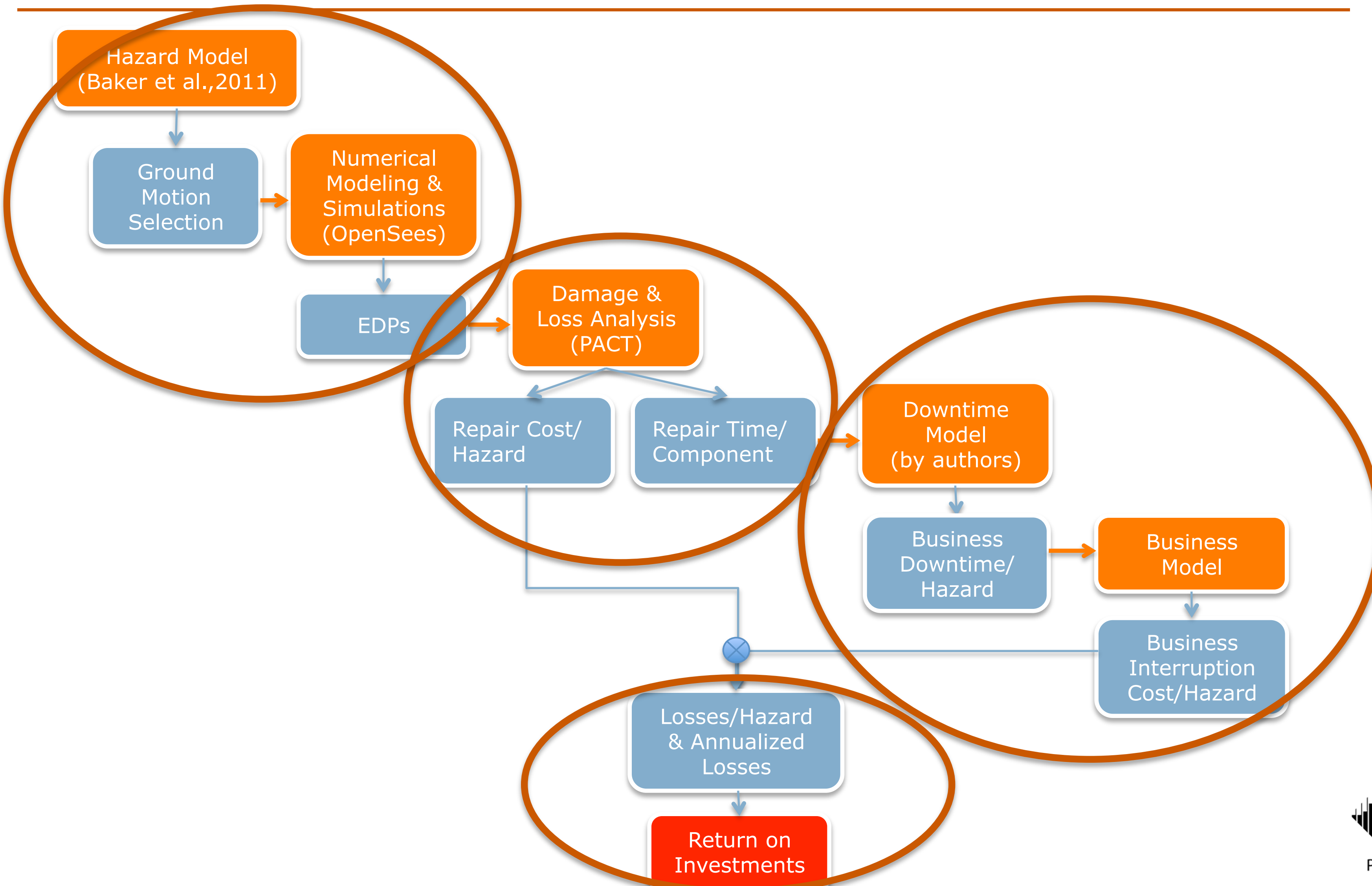
Work-flow of the analysis



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Numerical Model and Methods

- Analysis performed with OpenSees
- RHA performed on 2D frames
- Leaning column was modeled to account for P-Δ effects from the gravity columns
- Load: gravity loads & vertical and horizontal component of excitation
- Beams, columns, and braces modeled with nonlinear force-based fiber elements with low-cycle fatigue failure capabilities
- Damping modeled with Rayleigh damping utilizing damping ratio of 3%

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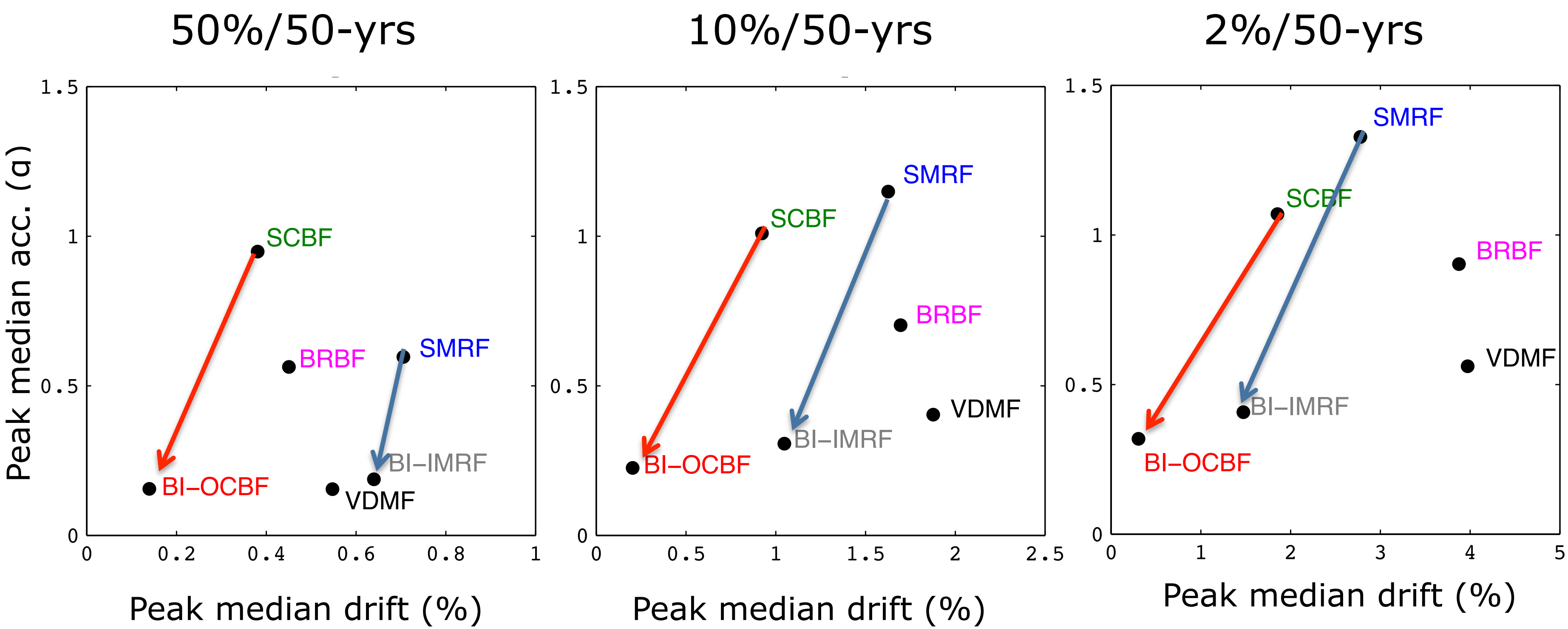
Structural Response:
Peak median drift vs. acceleration



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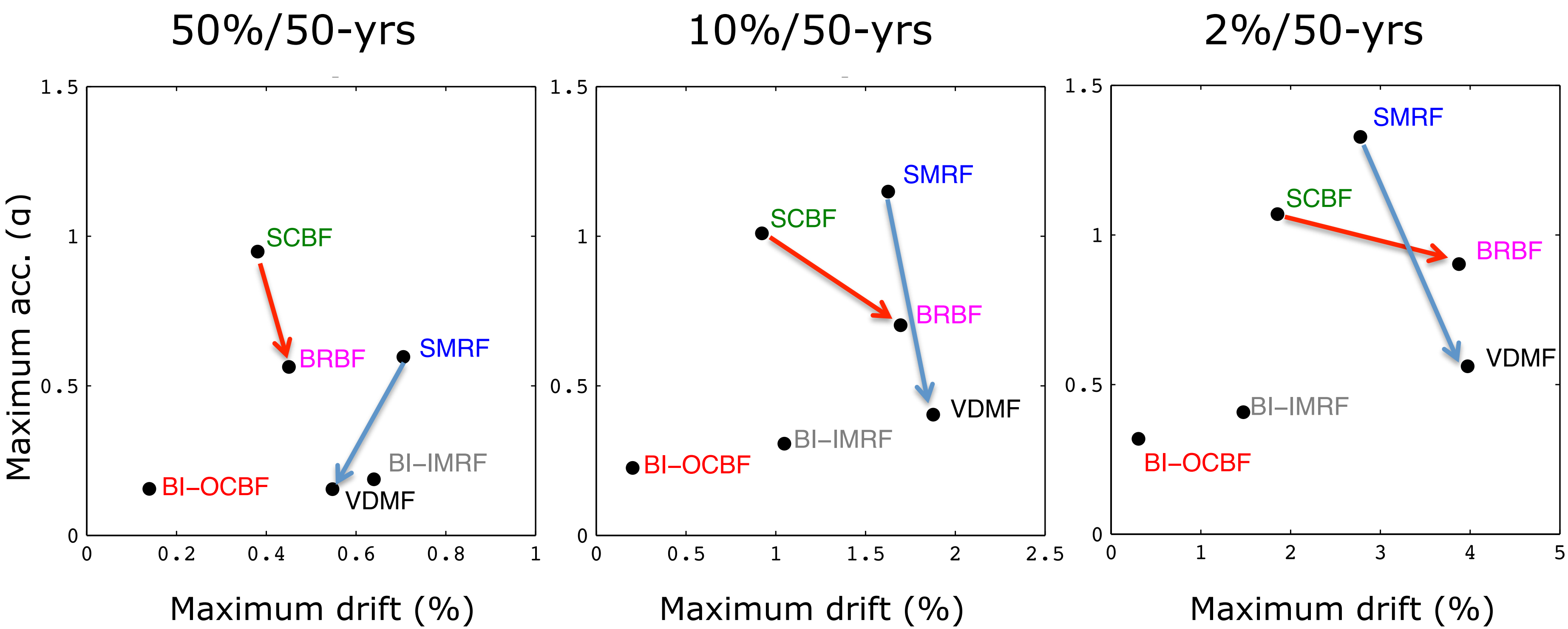
Structural Response:
Peak median drift vs. acceleration



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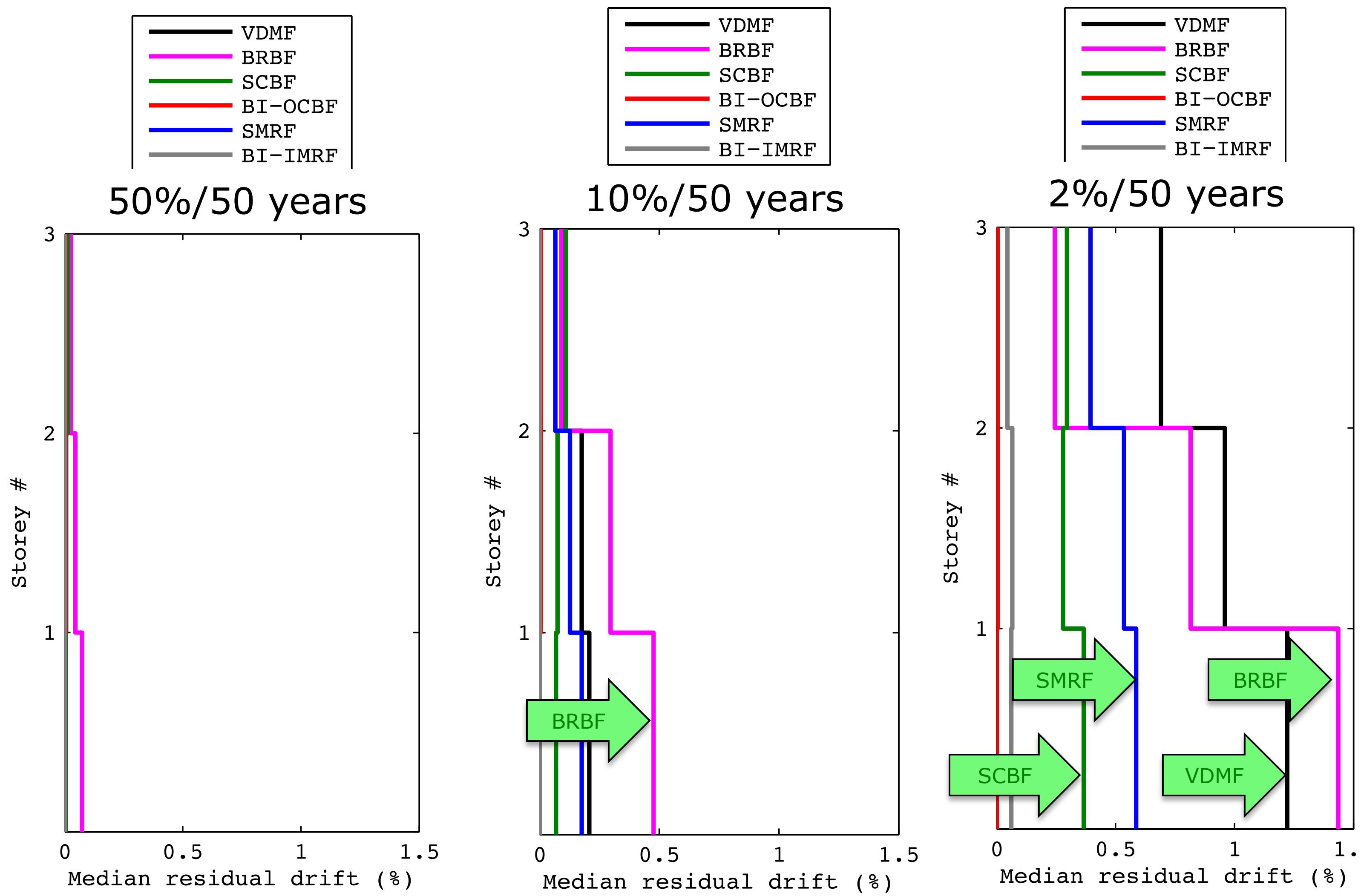
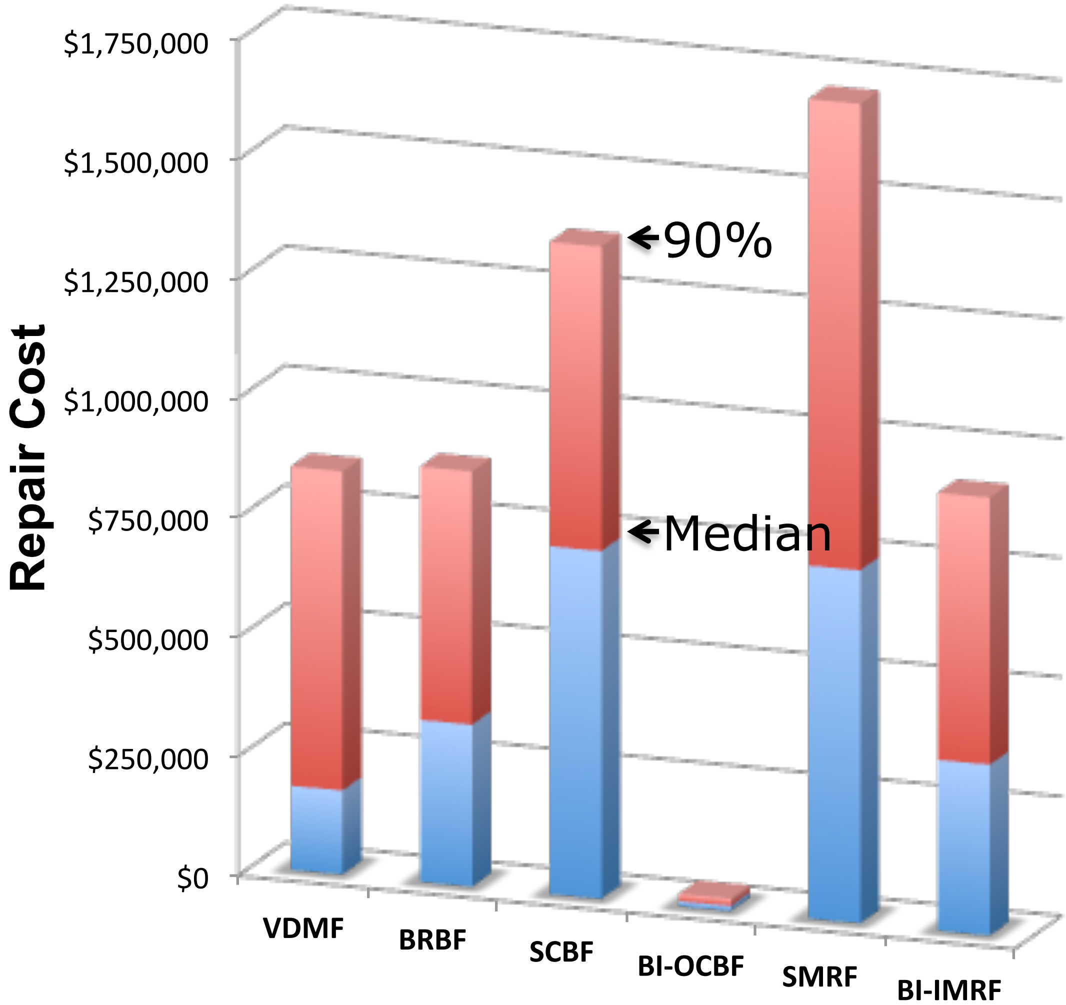
Structural Response:
Median Residual Drifts



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



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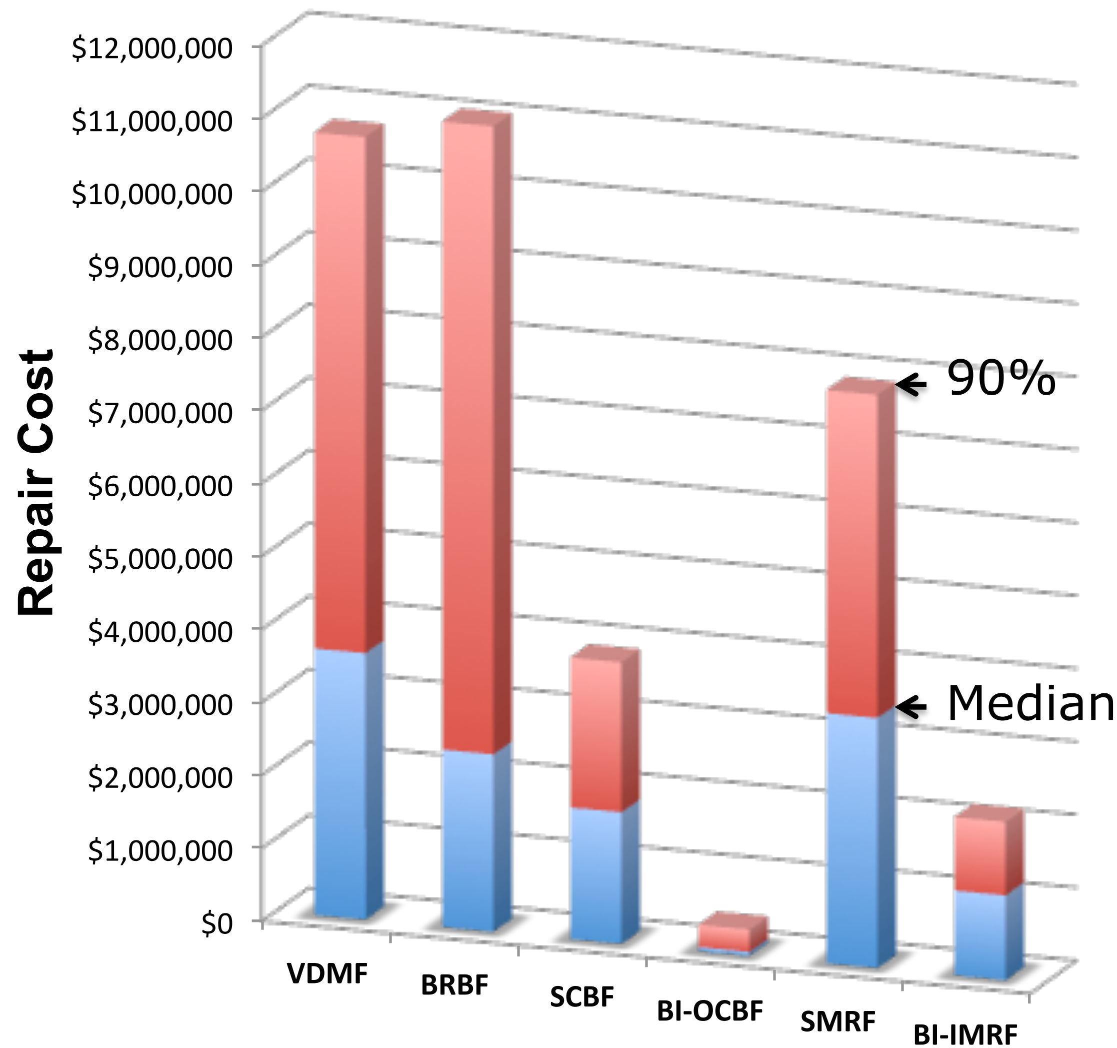
Repair Costs for scenario events:
Rare Earthquake (10%/50-yrs)



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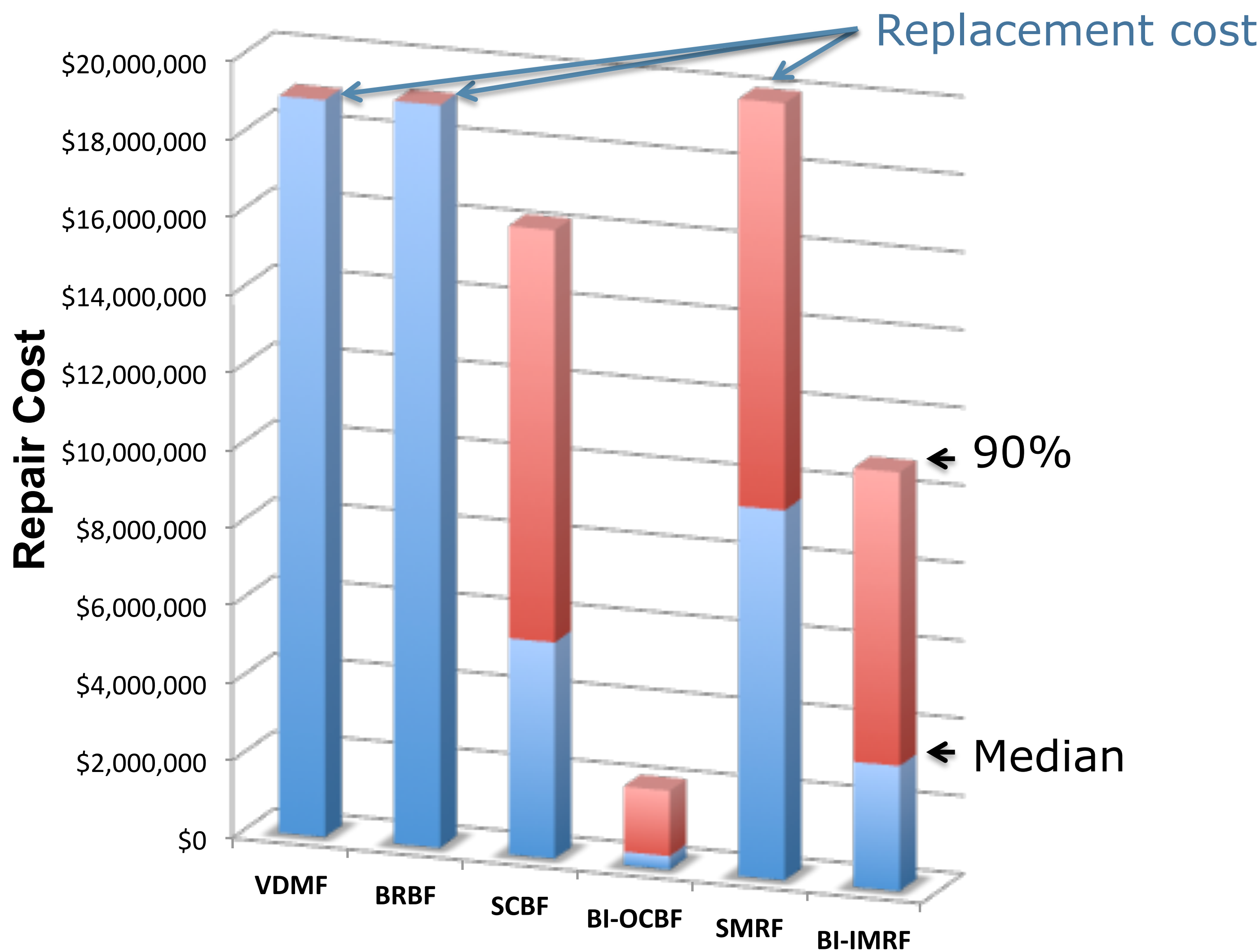
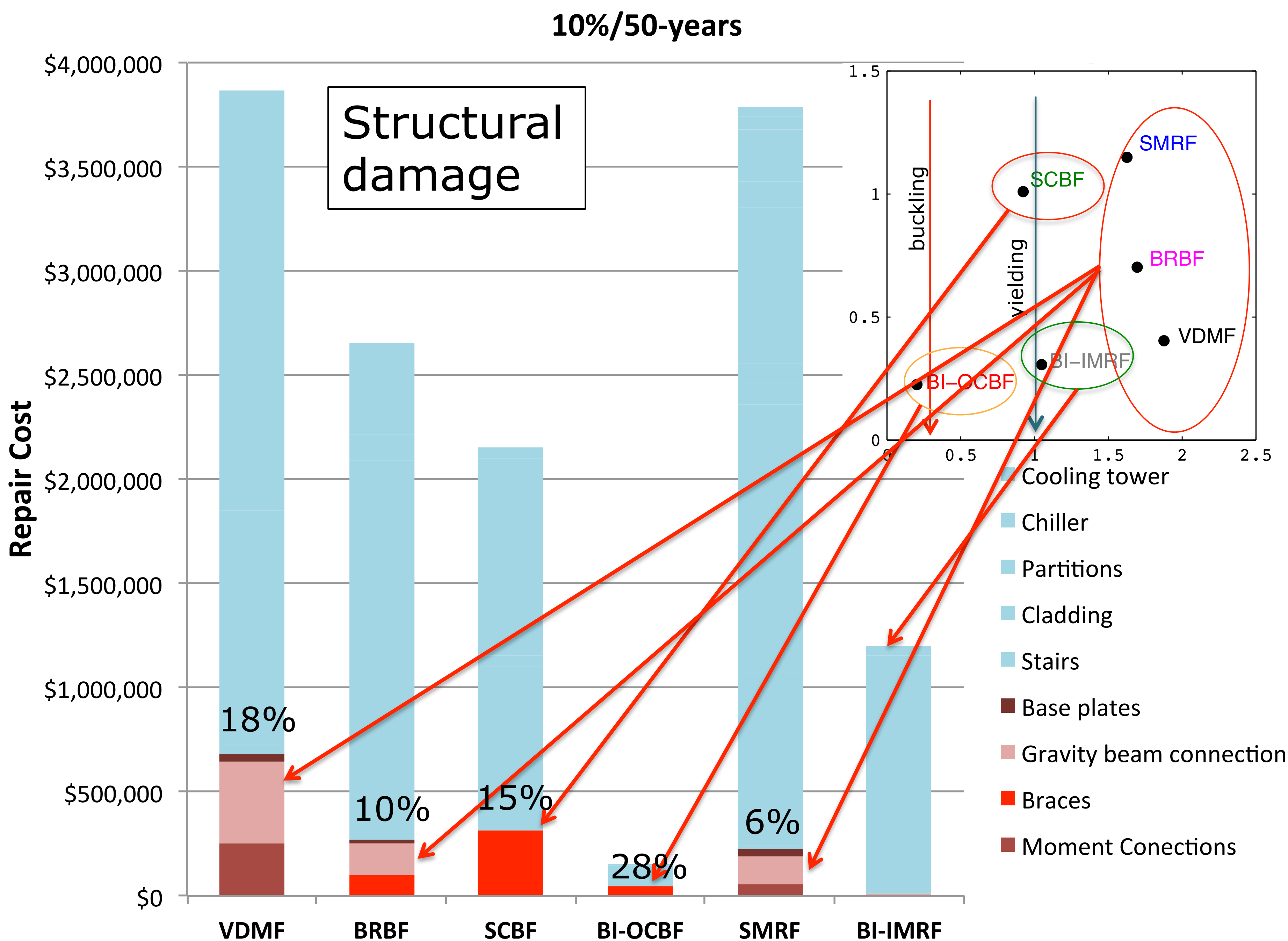
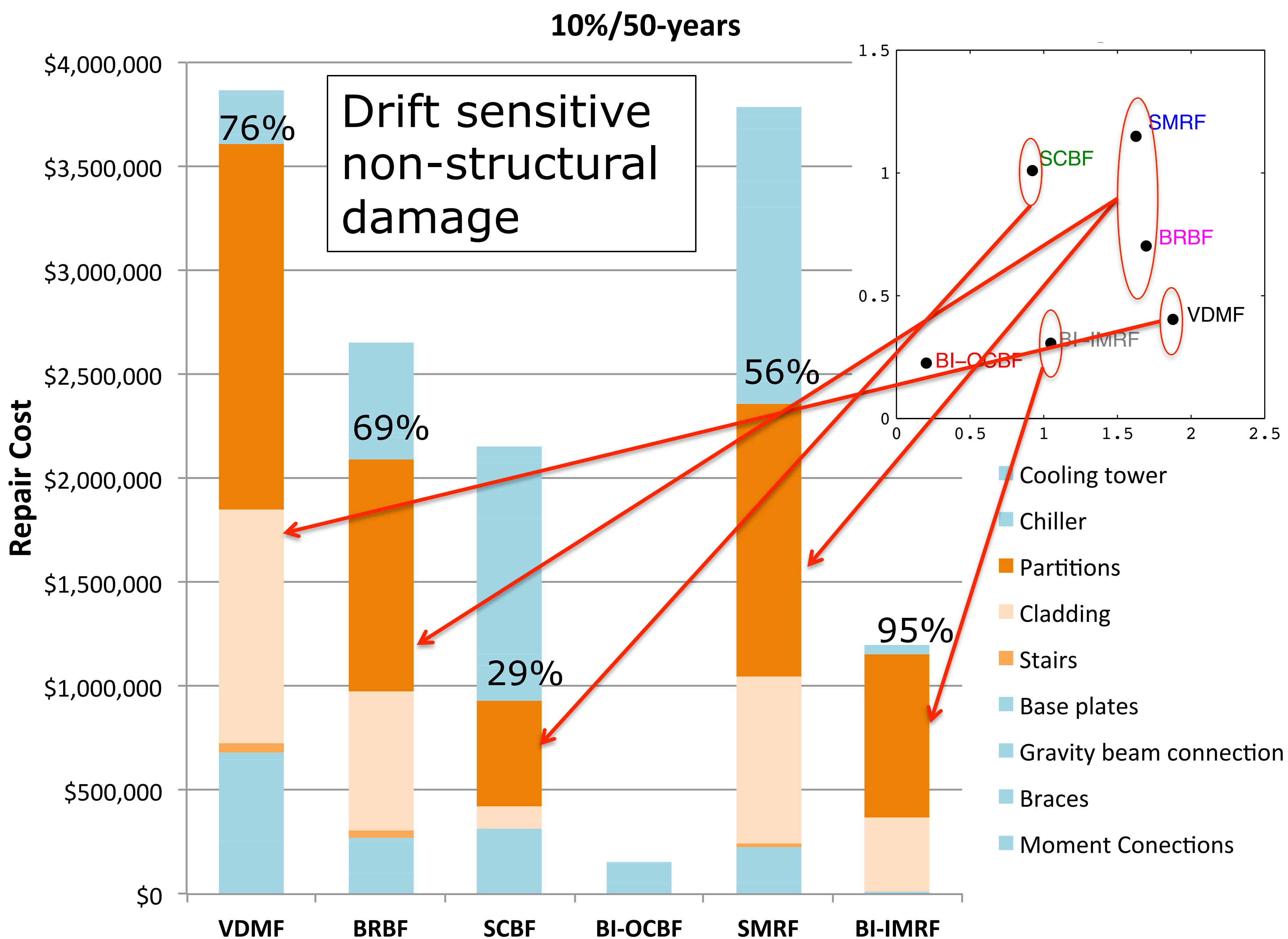
Repair Costs for scenario events:

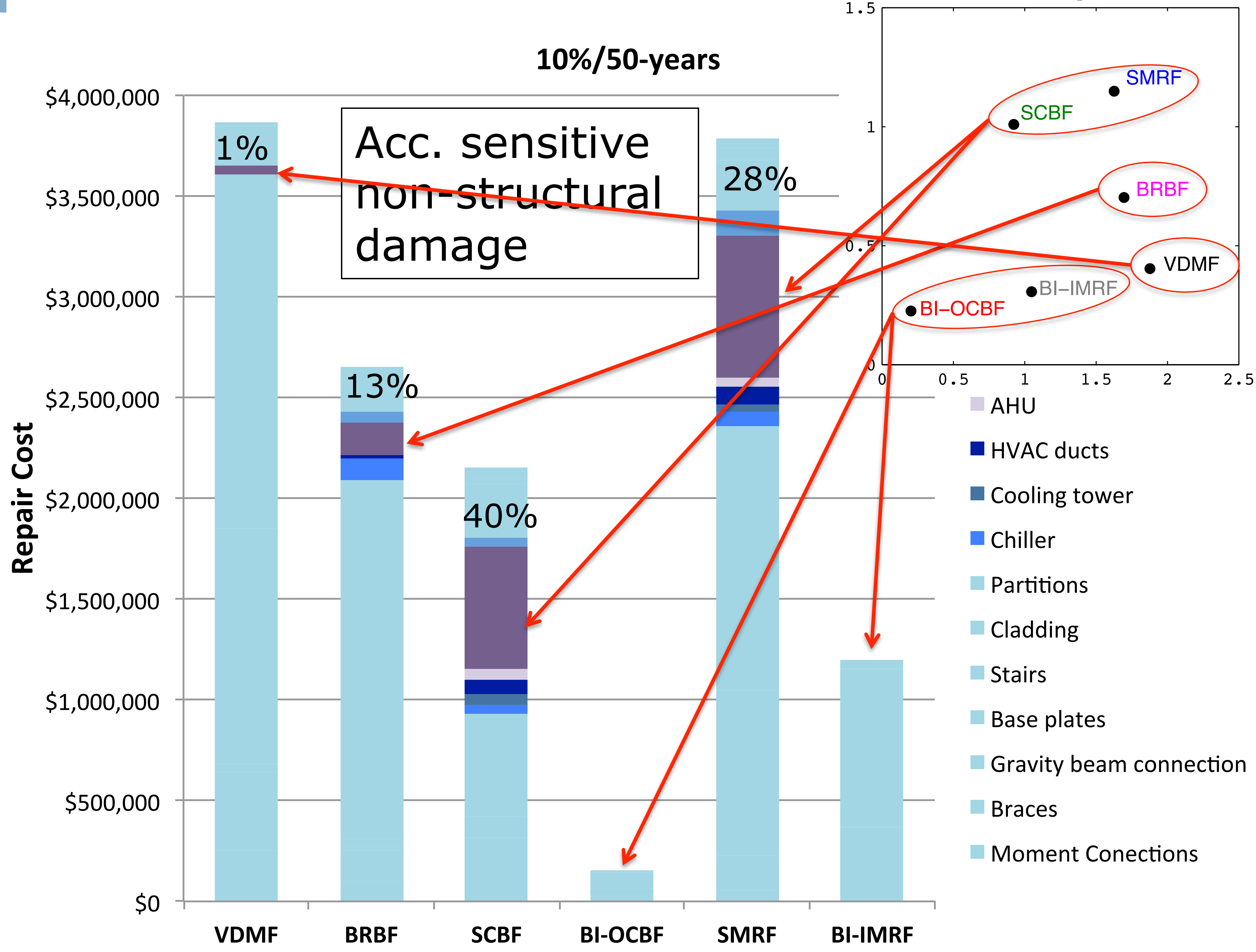
Very Rare Earthquakes (2%/50-yrs)

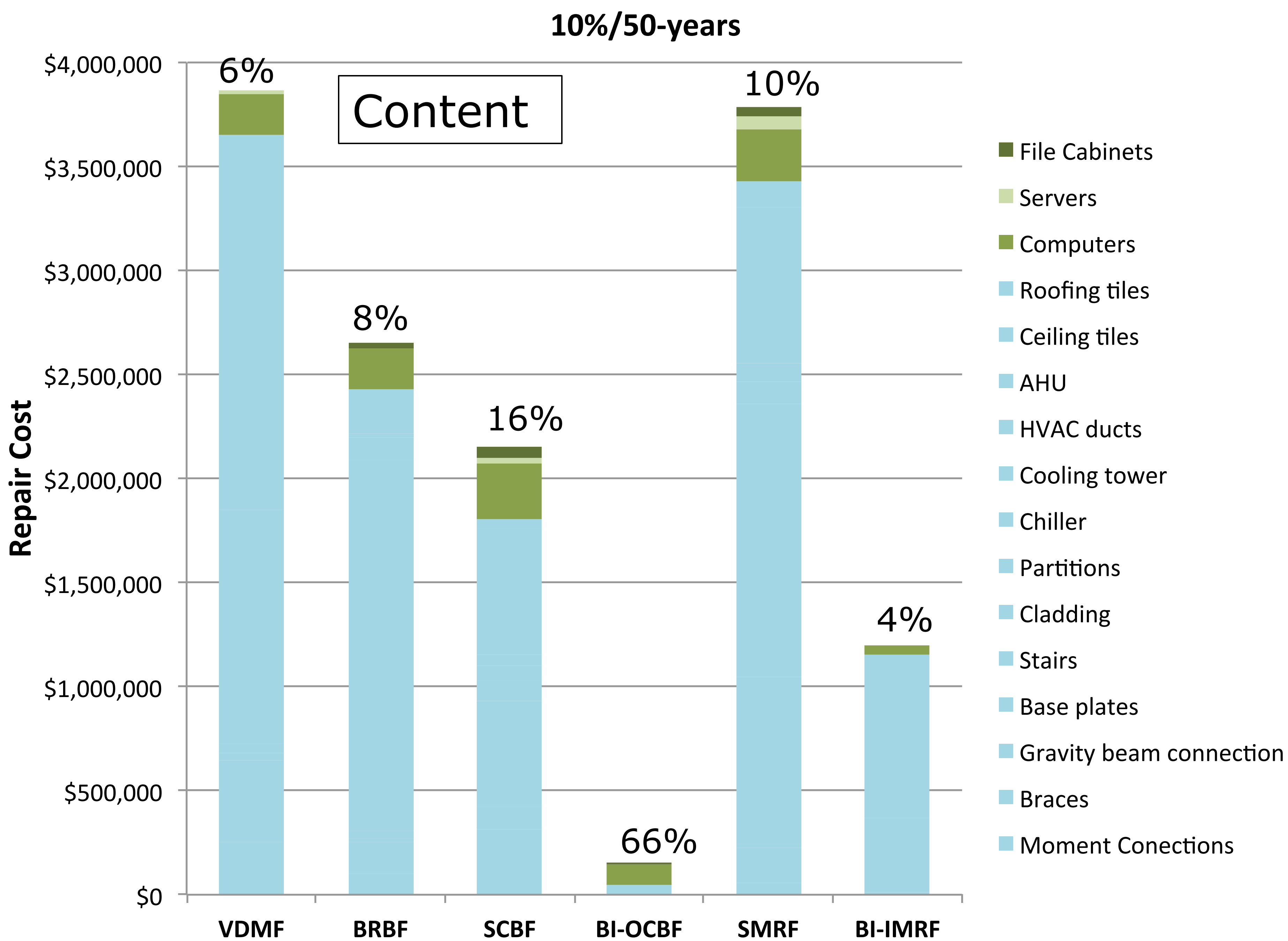



10%/50-years
Repair Cost
$4,000,000
$3,500,000
$3,000,000
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$0
Structural damage
18%
10%
15%
28%
6%
VDMF
BRBF
SCBF
BI-OCBF
SMRF
BI-IMRF
buckling
yielding
SMRF
SCBF
BRBF
VDMF
BI–IMRF
BI–OCBF
Cooling tower
Chiller
Partitions
Cladding
Stairs
Base plates
Gravity beam connection
Braces
Moment Conections



10%/50-years
Repair Cost
$4,000,000
$3,500,000
$3,000,000
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$0
VDMF
BRBF
SCBF
BI-OCBF
SMRF
BI-IMRF
76%
69%
29%
56%
95%
Drift sensitive non-structural damage
Cooling tower
Chiller
Partitions
Cladding
Stairs
Base plates
Gravity beam connection
Braces
Moment Conections
SMRF
SCBF
BRBF
VDMF
BI-IMRF
BI-OCBF
1.5
1
0.5
0
0.5
1
1.5
2
2.5

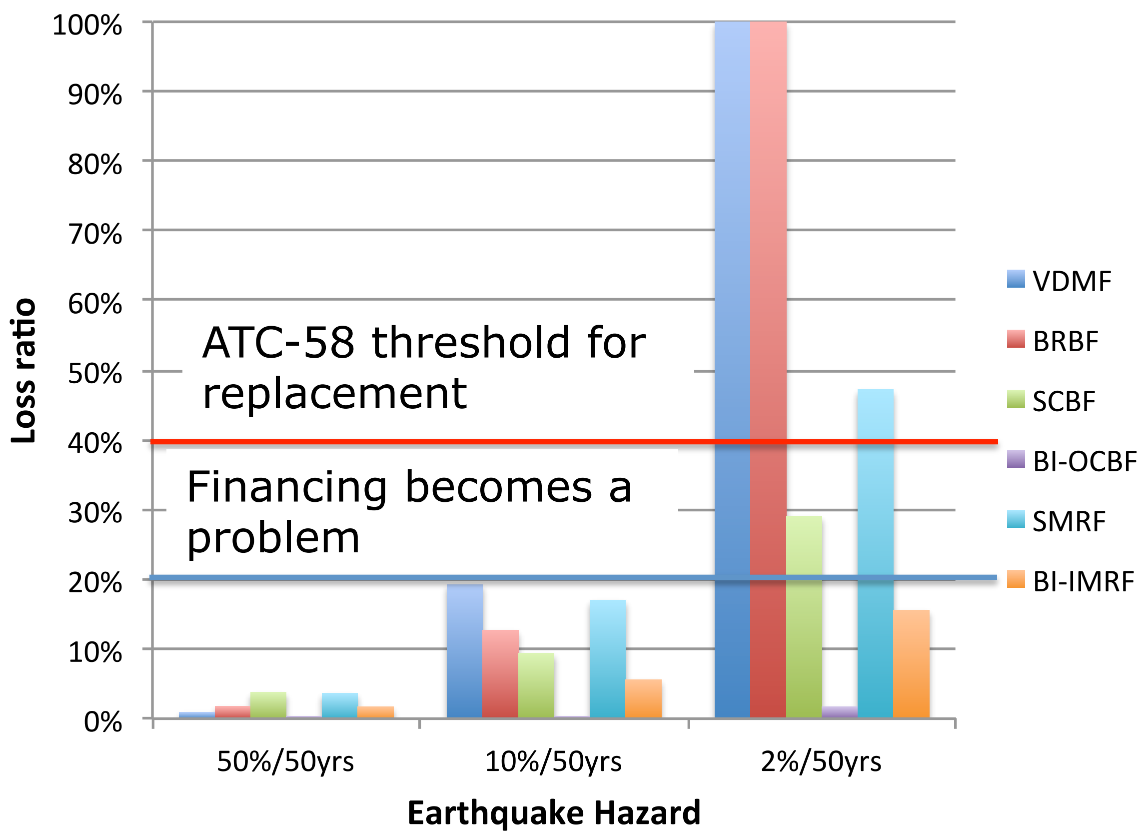

10%/50-years
Acc. sensitive non-structural damage
Repair Cost
$4,000,000
$3,500,000
$3,000,000
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$0
1%
13%
40%
28%
VDMF
BRBF
SCBF
BI-OCBF
SMRF
BI-IMRF
SMRF
SCBF
BRBF
VDMF
BI–IMRF
BI–OCBF
AHU
HVAC ducts
Cooling tower
Chiller
Partitions
Cladding
Stairs
Base plates
Gravity beam connection
Braces
Moment Conections


10%/50-years
Content
Repair Cost
$4,000,000
$3,500,000
$3,000,000
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$0
6%
8%
16%
66%
10%
4%
VDMF
BRBF
SCBF
BI-OCBF
SMRF
BI-IMRF
File Cabinets
Servers
Computers
Roofing tiles
Ceiling tiles
AHU
HVAC ducts
Cooling tower
Chiller
Partitions
Cladding
Stairs
Base plates
Gravity beam connection
Braces
Moment Conections

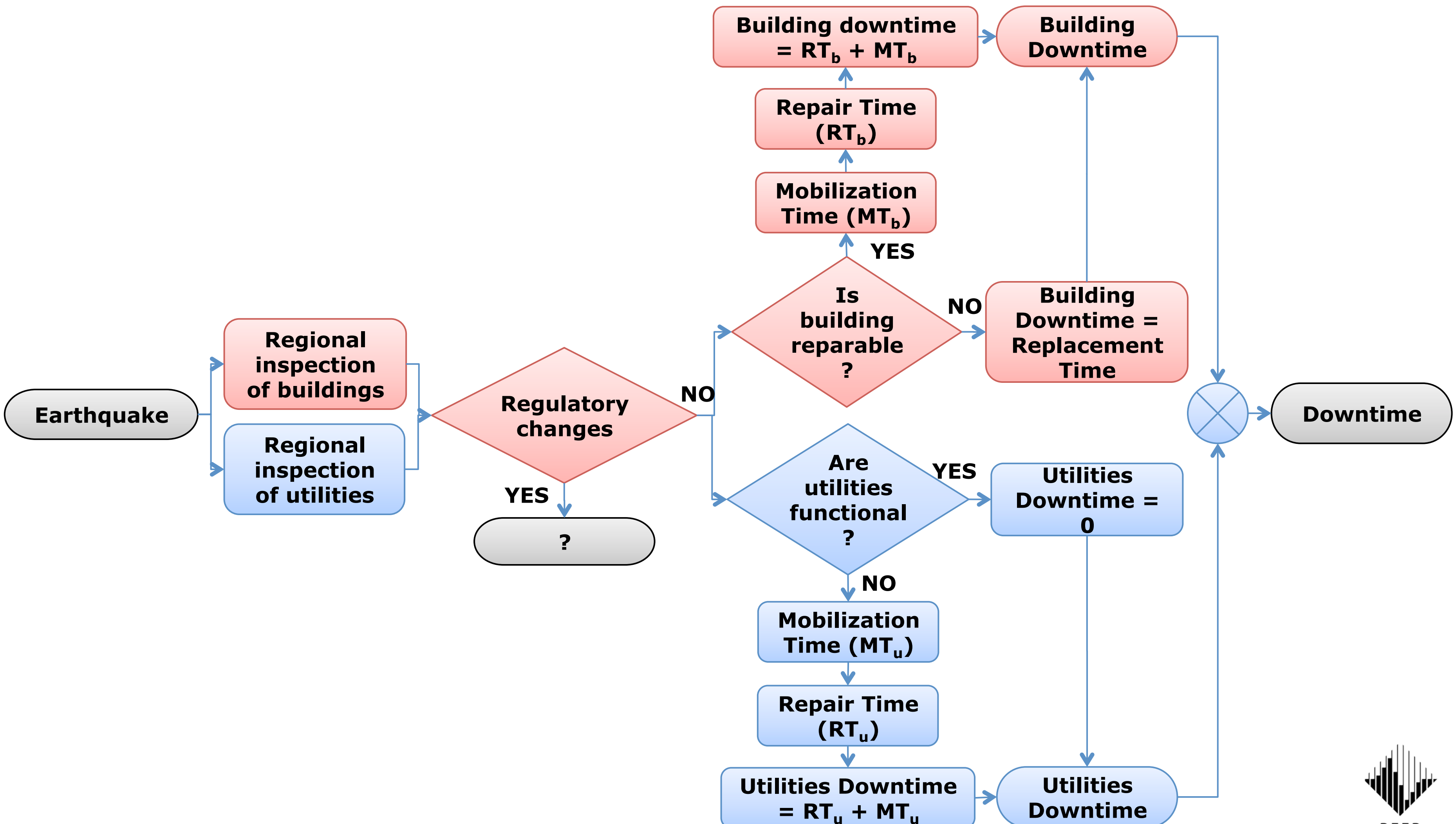
Repair Costs for scenario events:
Loss Ratio

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

Replacement Cost = 1.2 x Construction Cost



Business Downtime



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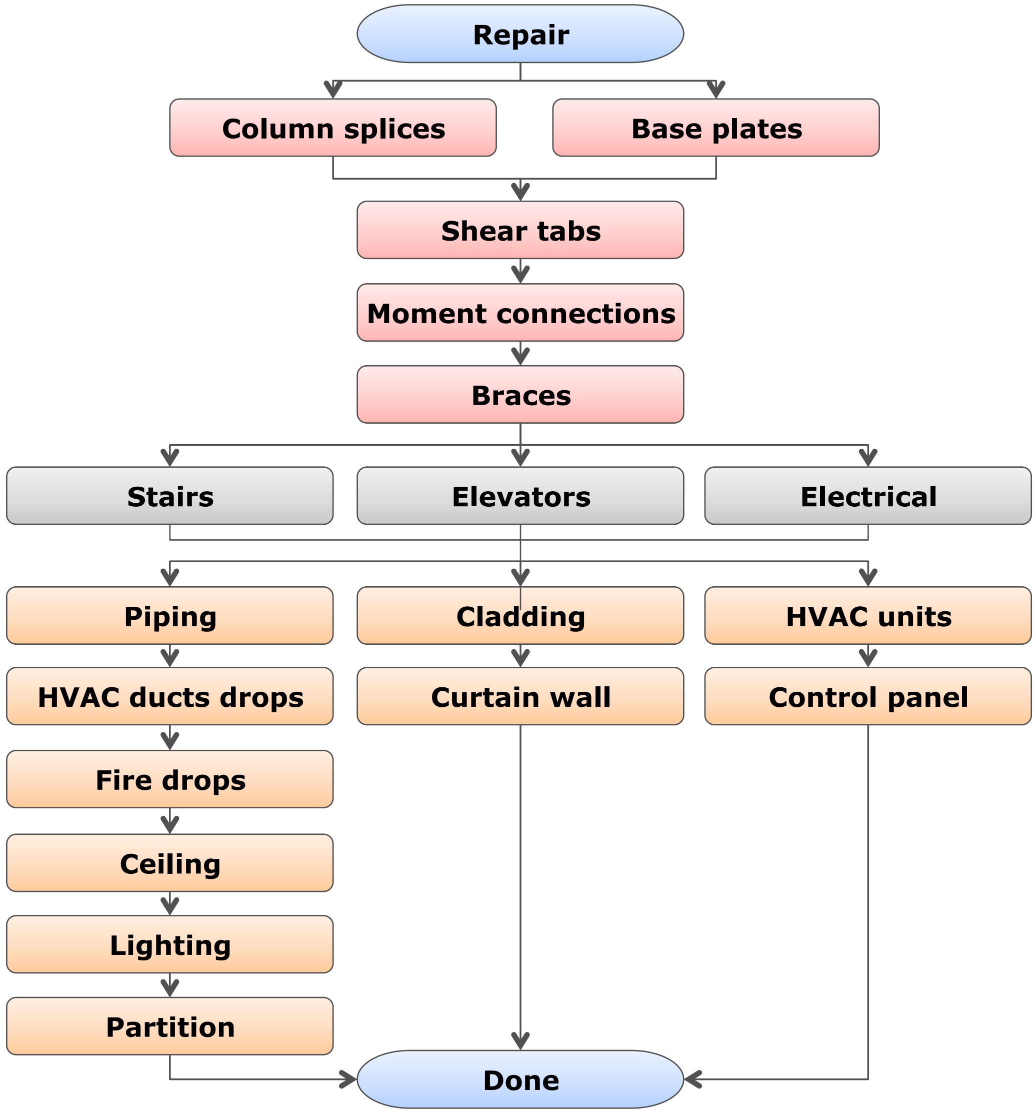
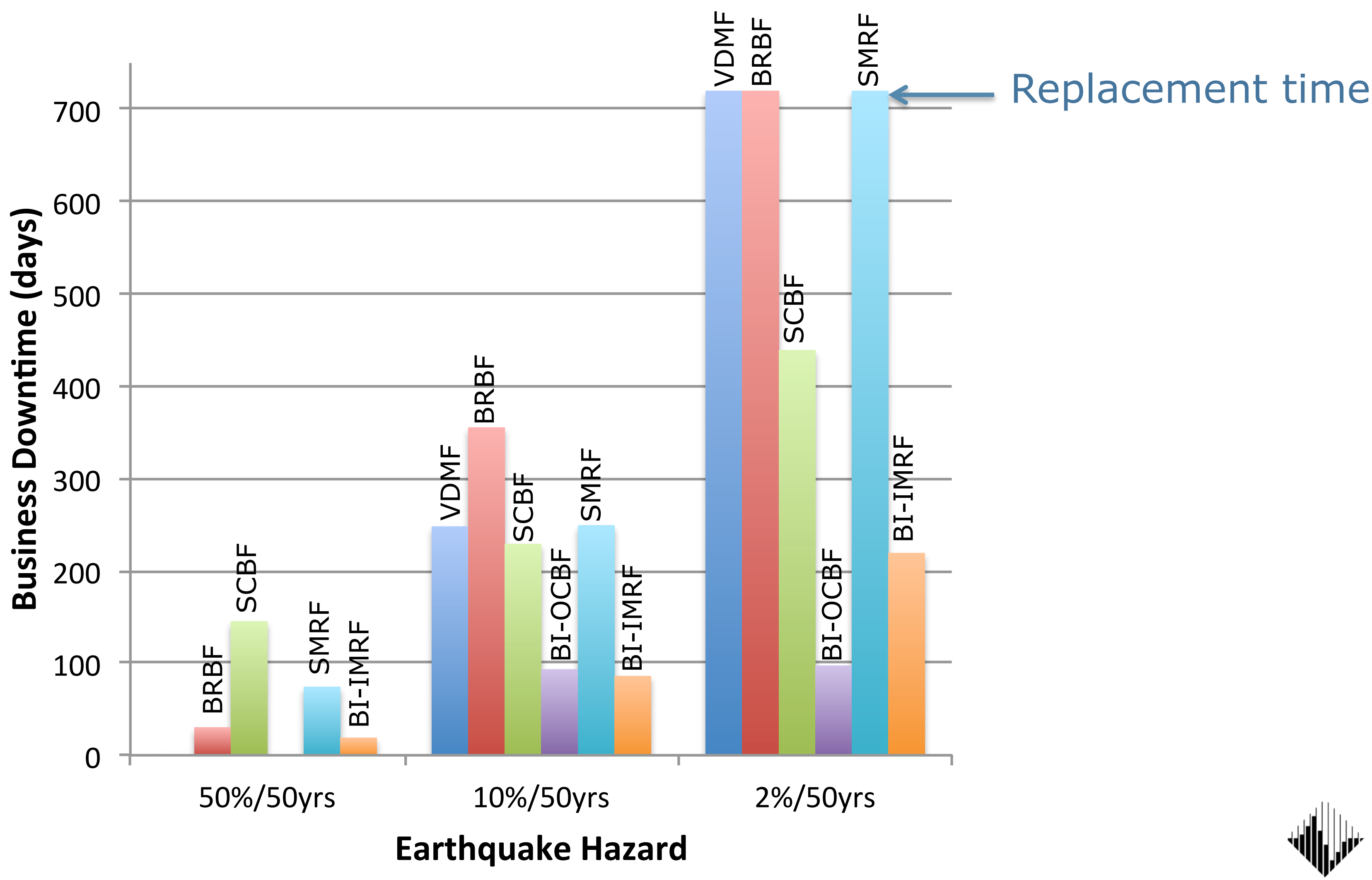
Repair time for functional recovery



Business Downtime



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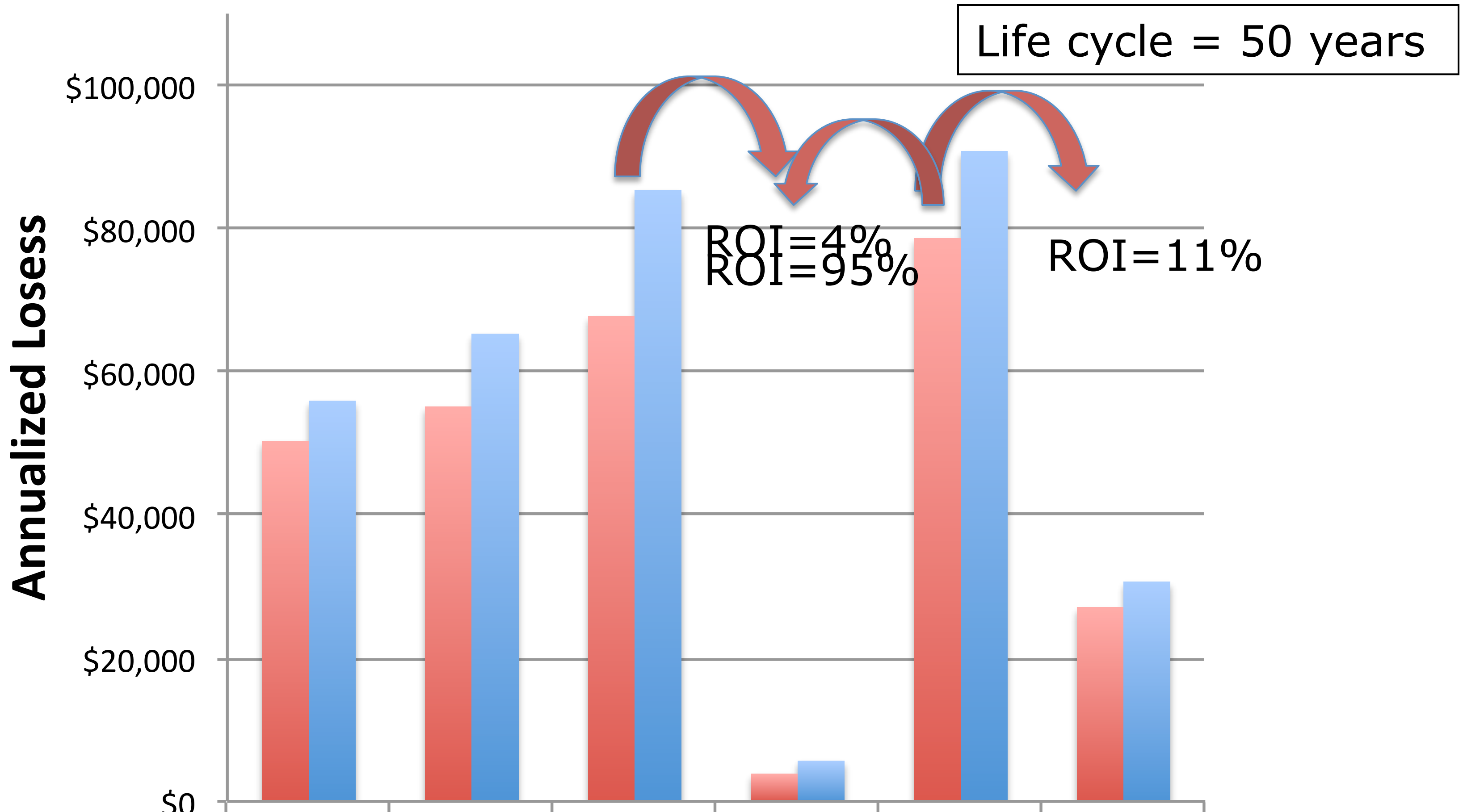
Approximate annualized losses



	VDMF	BRBF	SCBF	BI-OCBF	SMRF	BI-IMRF
Oakland	$50,326	$55,123	$67,727	$3,867	$78,651	$27,089
Los Angeles	$55,912	$65,264	$85,321	$5,681	$90,788	$30,654

Conclusions

- Losses of different code compliant structural system range from $4,000 to $90,000
- Nonstructural damage dominates the losses
- PBEE methodology should be used in design to mitigate damage, reduce the losses, and to optimize owners return on investment
- Question:

  Can we afford to seismically isolate?
- Answer:

  Can we afford not to?

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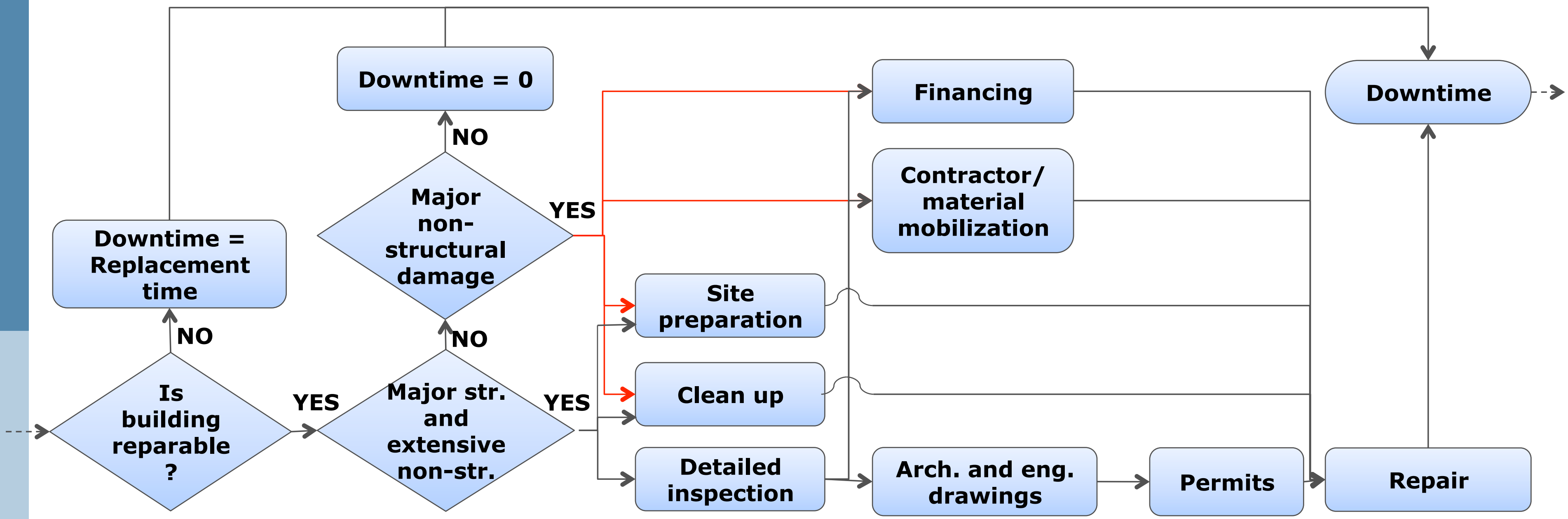
Building Downtime



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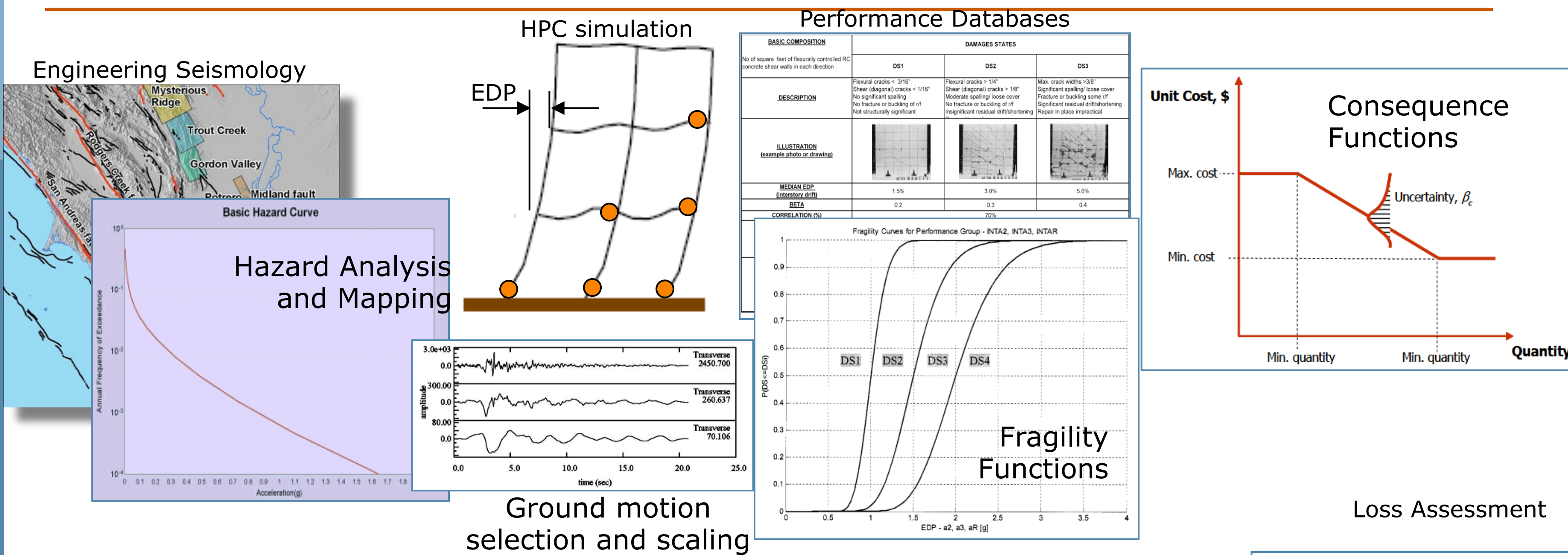
Holistic risk-oriented view:
Performance-Based Seismic Design

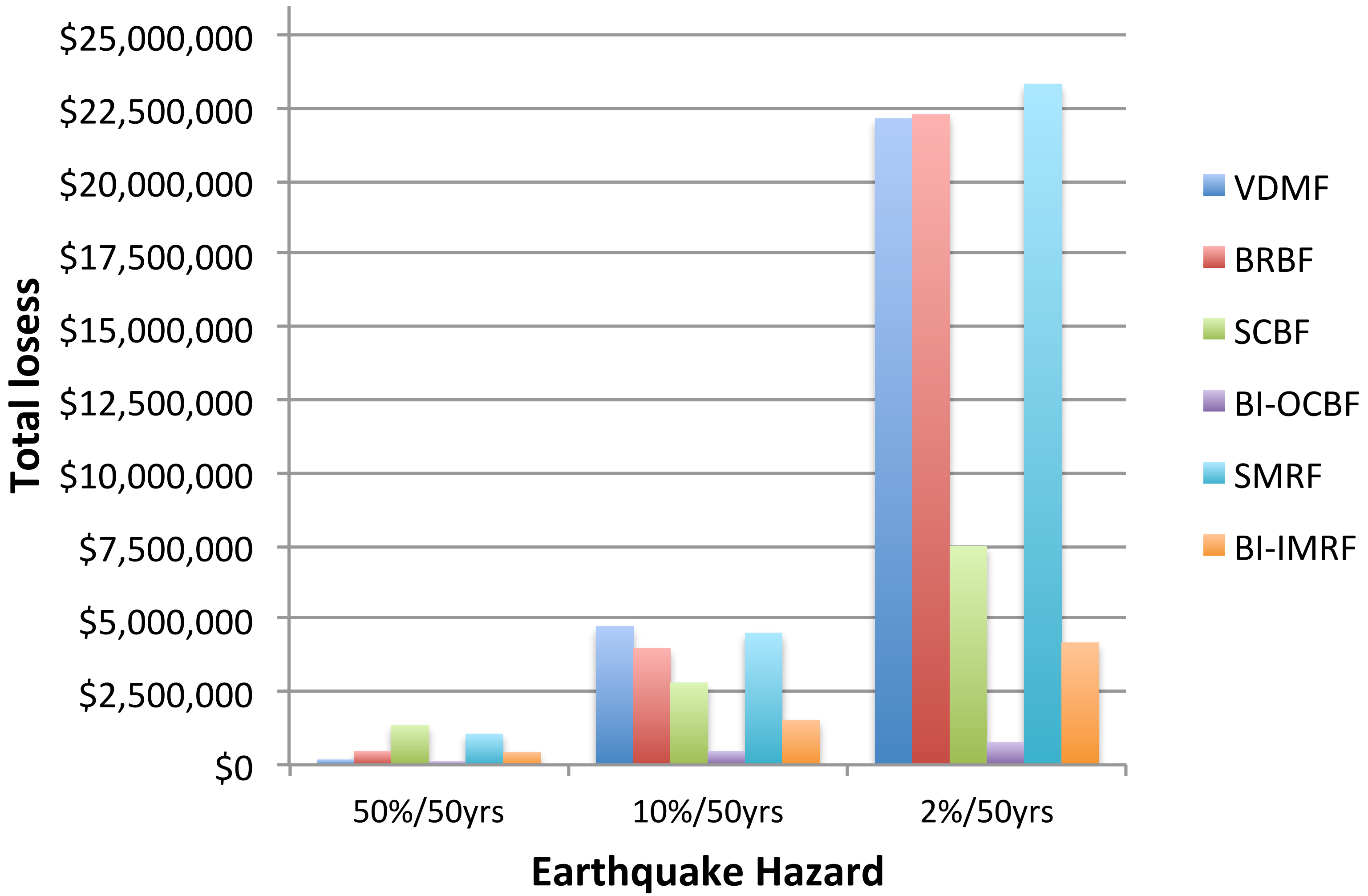


Seismic Hazard Analysis	→	Response Analysis	→	Damage Analysis	→	Loss Analysis
$\lambda(im)$		$G(edp \mid im)$		$G(dm \mid edp)$		$G(dv \mid dm)$
IM: intensity measure		**EDP**: Engineering Demand Parameter		**DM**: Damage Measure		**DV**: Decision Variable

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

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

Total losses



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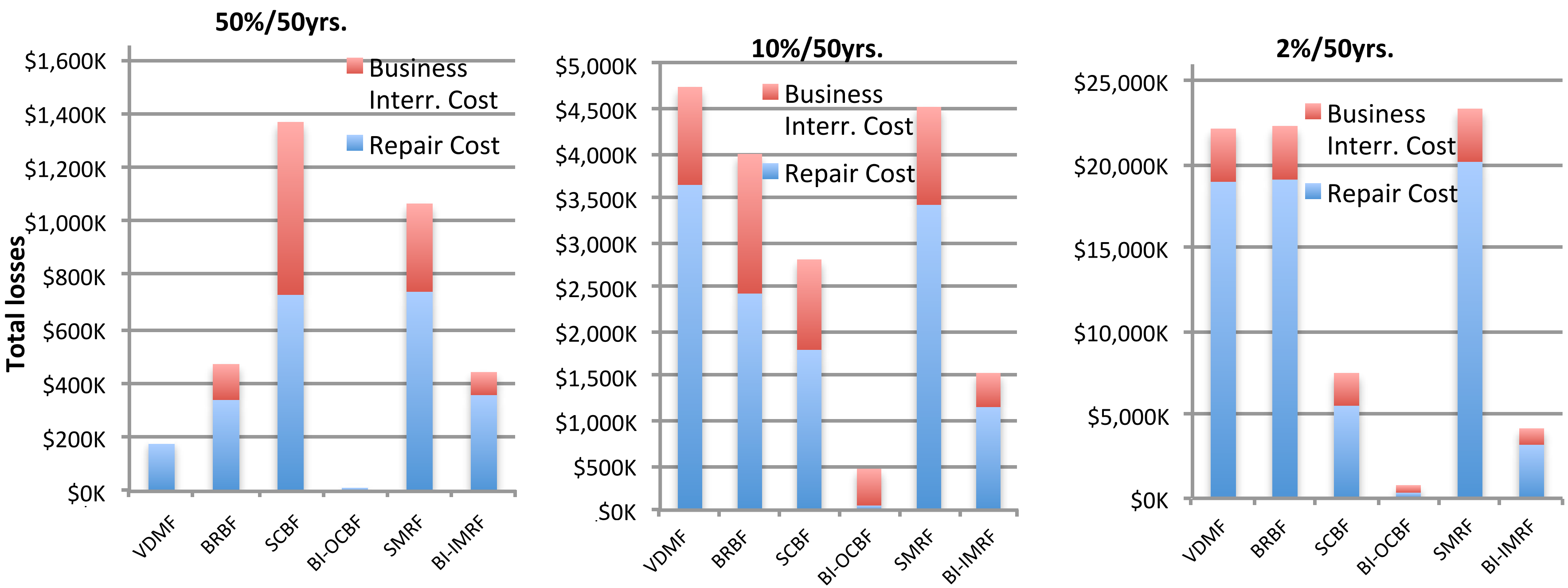
Indirect and Direct Losses: Oakland



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Return on Investments

- Inflation rate is assumed to be 3%
- Return on investments is:
  - BI-OCBF relative to SCBF (investment was 6% of the construction cost of SCBF):
    - 3.4% for Los Angeles
    - 4.6% for Oakland
  - BI-IMRF relative to SMRF (investment was 2.3% of the construction cost of SMRF):
    - 12.3% for Los Angeles
    - 10.1% for Oakland

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