Life-Cycle Costs of Steel Frame Buildings Subjected to Earthquake Loading

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Mozarella di bufala

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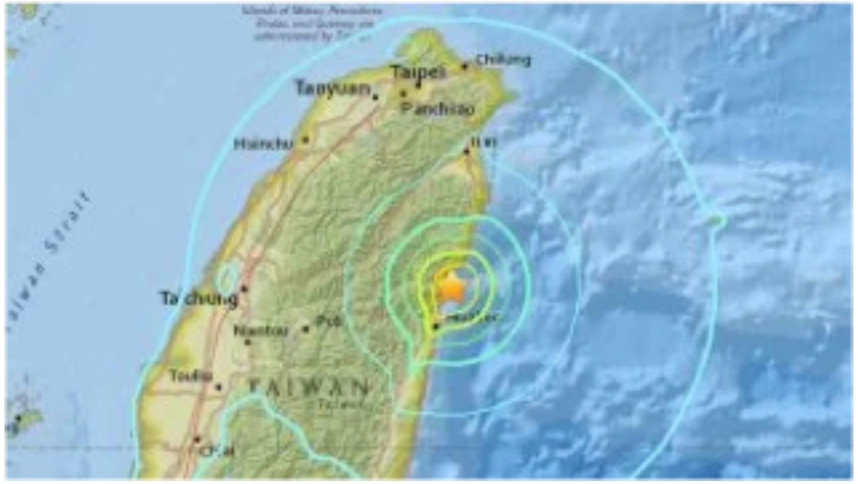
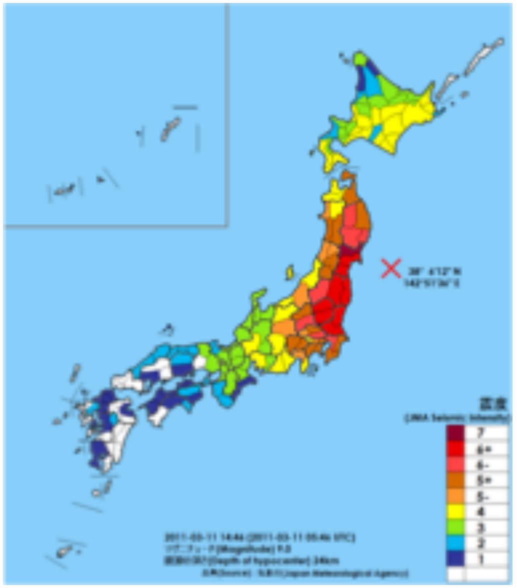
Motivation – Collapse Risk Quantification

-Low-Probability of Occurrence Seismic Events



Taiwan 2018



Hyogoken-Nanbu 1995

Motivation

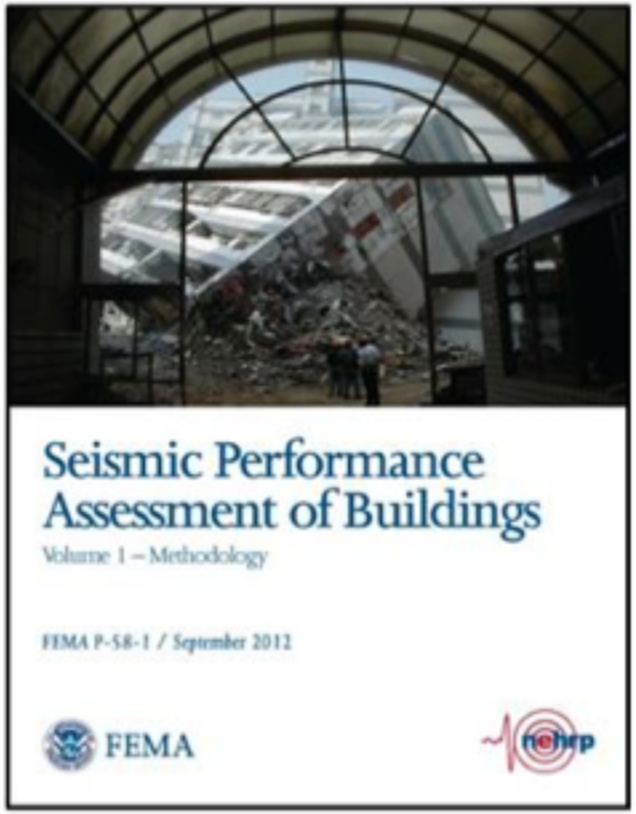
-Earthquake-induced Losses of Code-Conforming Steel Buildings

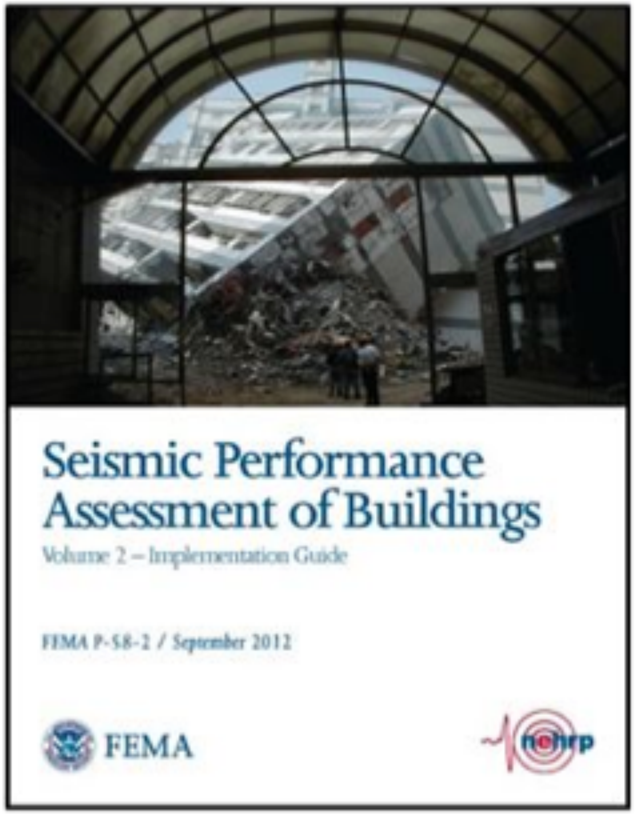
- ☆ Frequently occurring seismic events:
  - ☆ damage to non-structural content
- ☆ Low-Probability of occurrence seismic events:
  - ☆ Hopefully “no collapse” but likely “residual deformations”

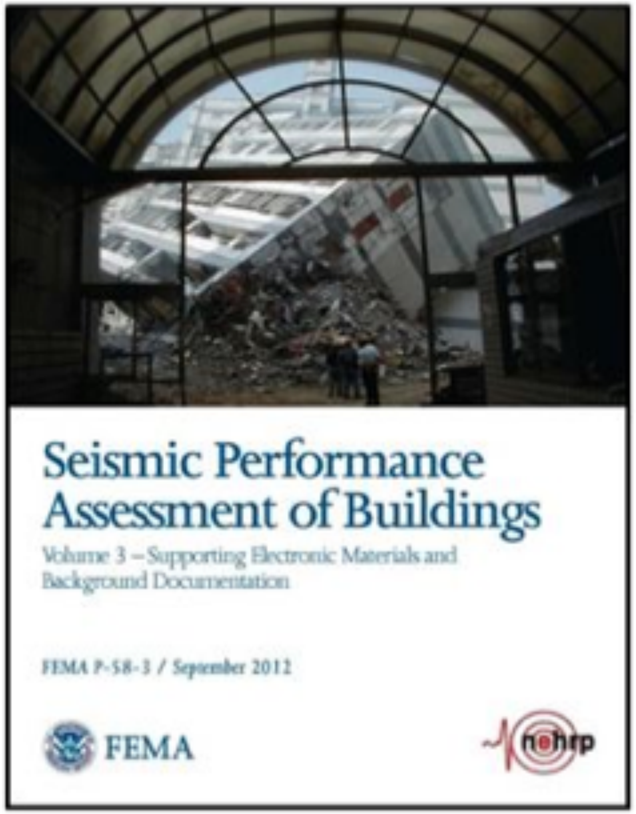
Source: Bruneau et al. (2011)

Source: Kumamoto 2016, Japan

Motivation
-Earthquake-induced Loss Assessment







Source: FEMA P58

Overview of PBEE Methodology

$$\lambda(DV) = \int_{\substack{all\\IMs}} \int_{\substack{all\\EDPs}} \int_{\substack{all\\DMs}} G(DV|DM)\,dG(DM|EDP)\,dG(EDP|IM)\,d\lambda(IM)$$

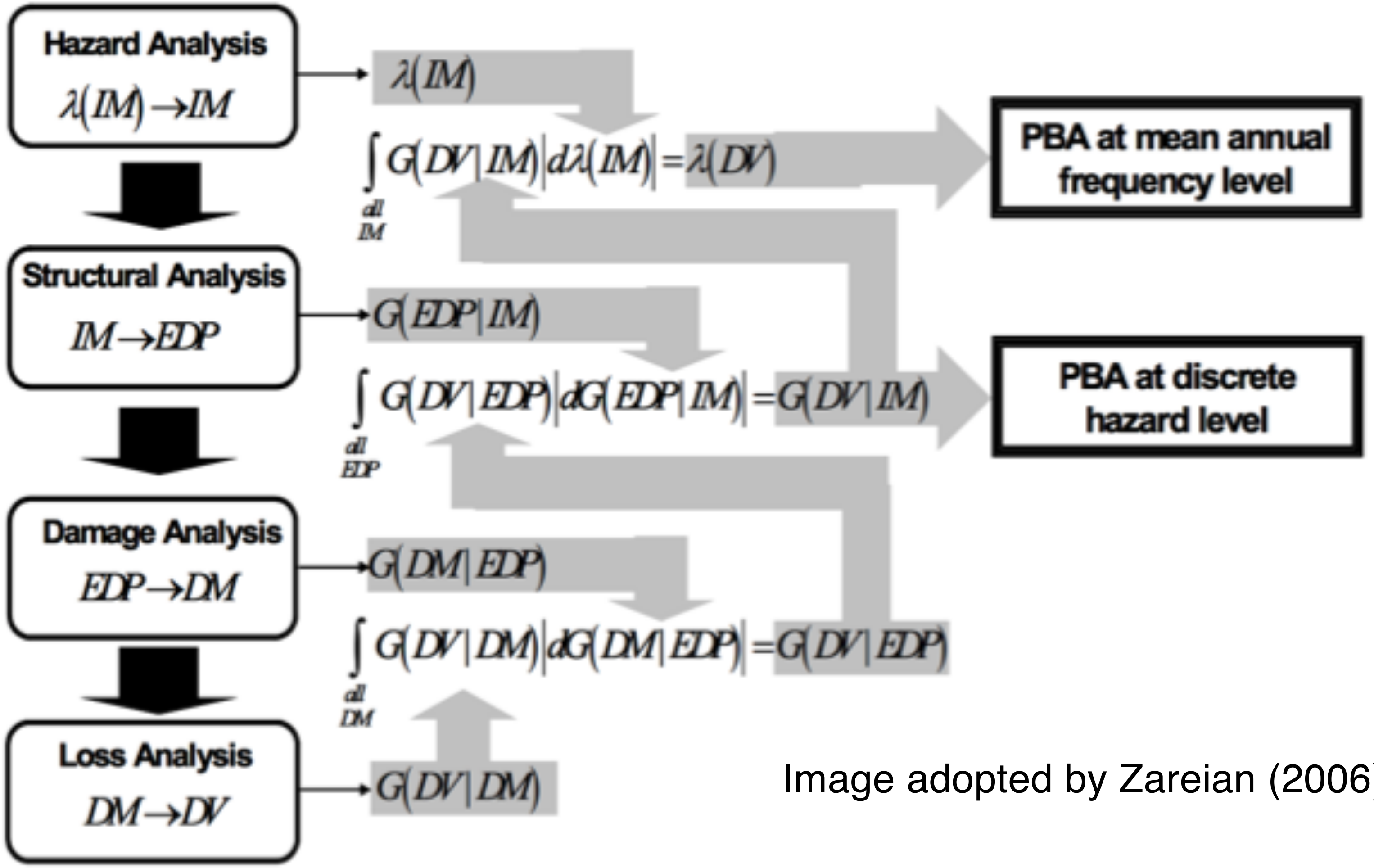
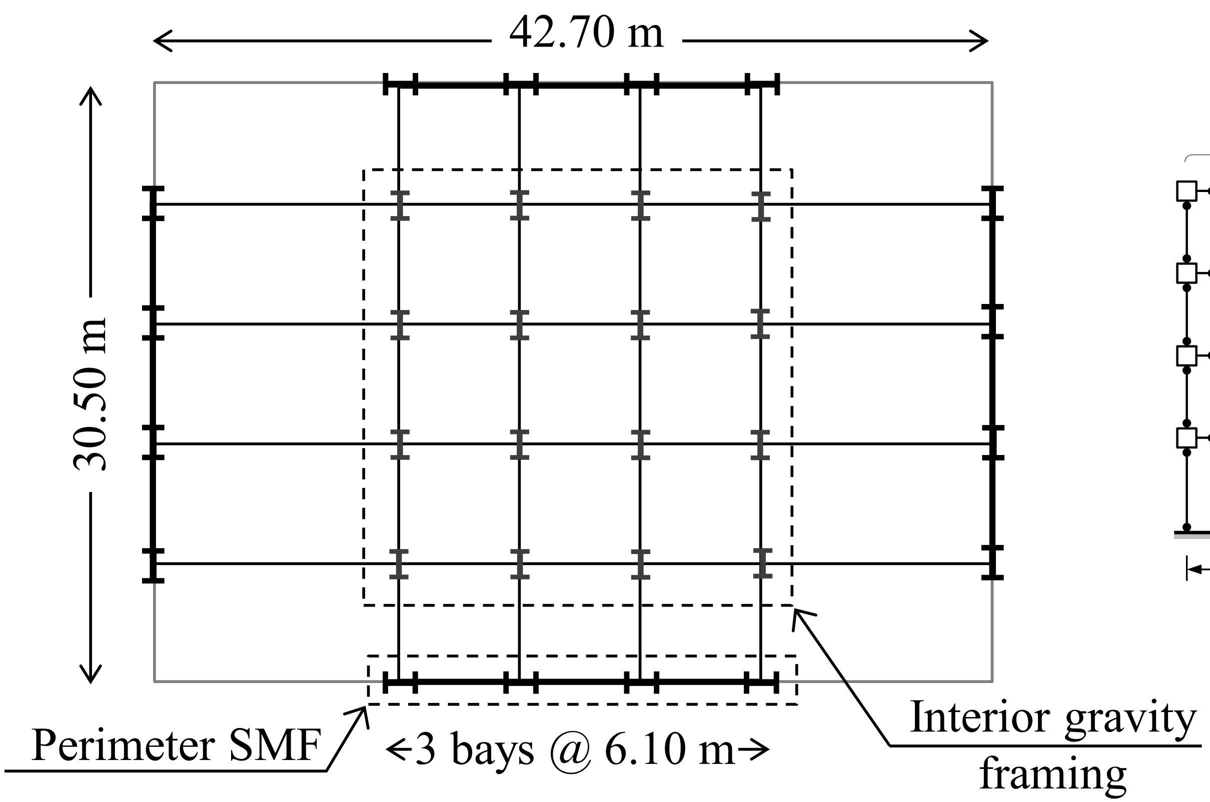
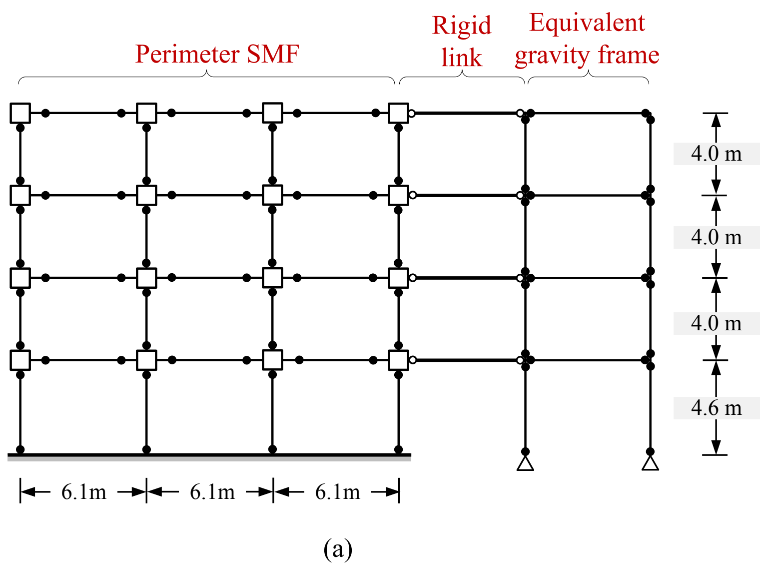


Image adopted by Zareian (2006)

Motivation
-Impact of Numerical Model Representation

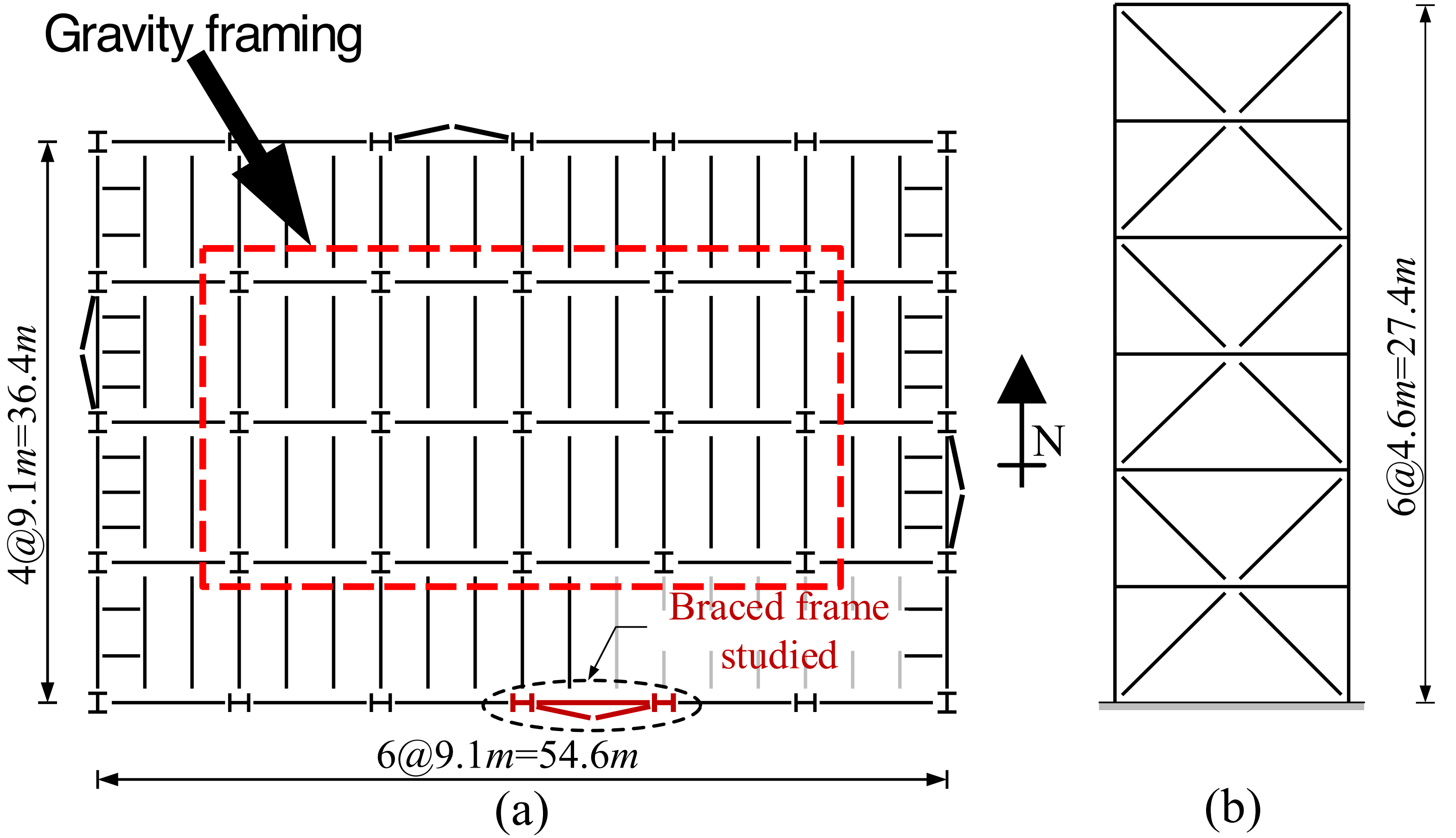
Historically, "bare frame" models have been utilized for nonlinear response history analysis of frame buildings (e.g., Composite action, gravity framing is ignored).





Motivation
-Impact of Numerical Model Representation

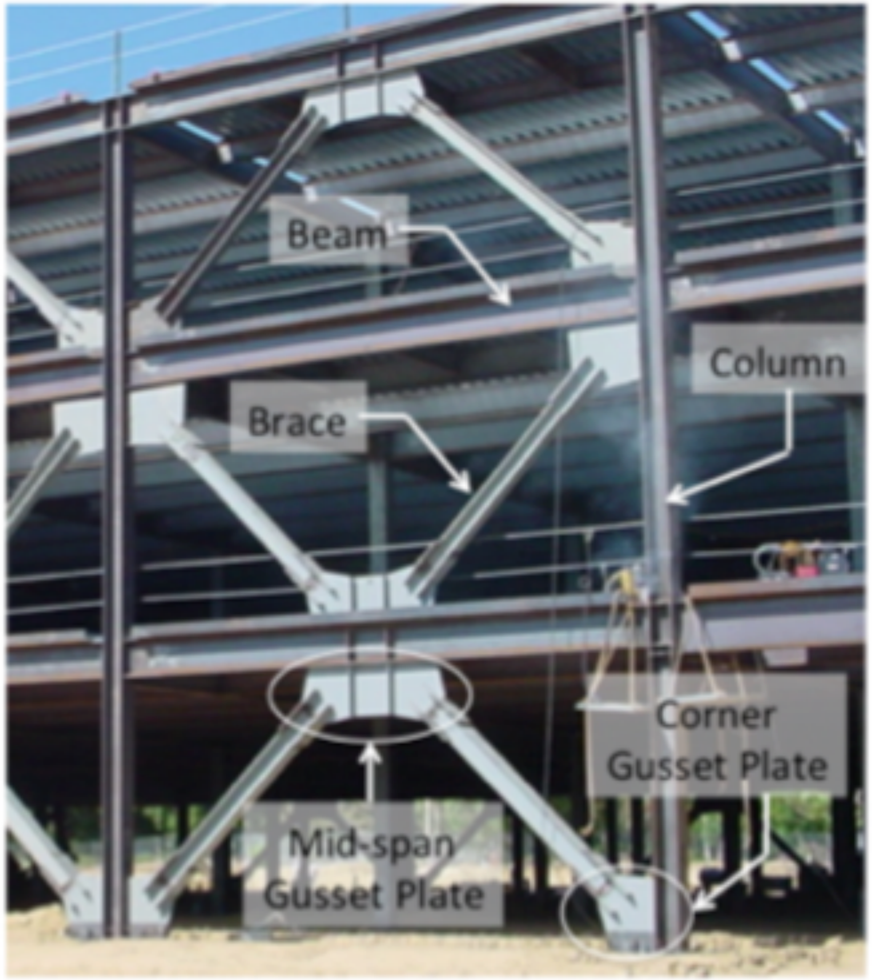
- ☆ Seismic performance assessment: typically with "bare-frame" models
- ☆ Composite action, gravity framing typically ignored



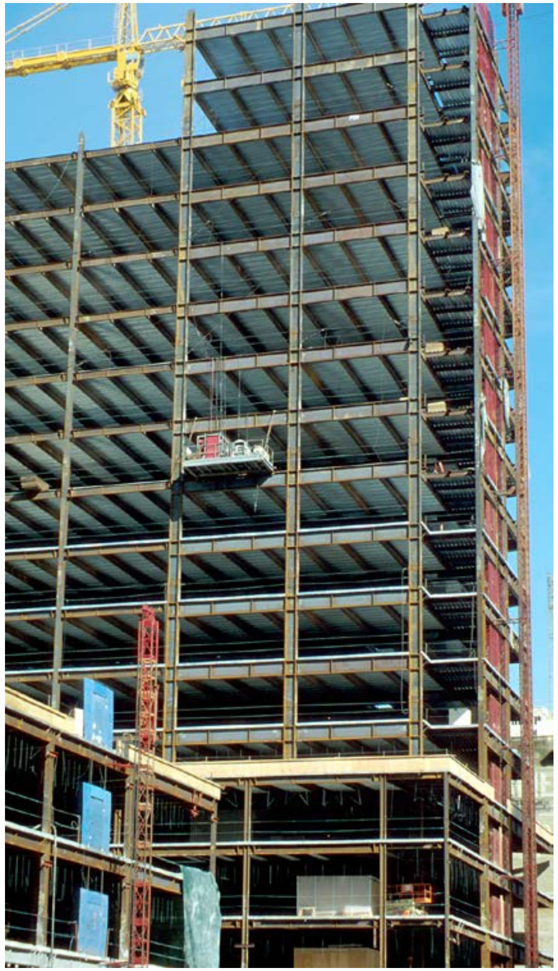
Problem Statement

Comprehensive Loss Assessment of Steel Frame Buildings

Steel Special Concentrically Braced Frames



Steel Special Moment Frames



Images courtesy of Prof. M. Engelhardt

Objectives and Scope

- ✧ Utilize loss metrics in order to quantify the seismic-induced losses in steel frame buildings designed in seismic regions.
- ✧ Assess the effect of analytical model representation of a steel frame building on earthquake-induced losses under various seismic intensities.
- ✧ Quantify the effect of residual deformations on the loss assessment of steel frame buildings with steel MRFs and SCBFs.
- ✧ Assess the effect of seismic design parameters (e.g., SCWB ratio) on the earthquake-induced losses of steel frame buildings in highly seismic regions.

Overview of Loss Estimation Methodology

$$E\left[L_T \middle| IM\right] = \underbrace{E\left[L_T \middle| NC \cap R, IM\right] \cdot P\left(NC \cap R \middle| IM\right)}_{\text{Loss given that collapse does not occur and the building will be repaired}} + \underbrace{E\left[L_T \middle| NC \cap D\right] \cdot P\left(NC \cap D \middle| IM\right)}_{\text{Loss due to building demolition given no collapse but due to large residual deformations}} + \underbrace{E\left[L_T \middle| C\right] \cdot P\left(C \middle| IM\right)}_{\text{Loss when collapse occurs}}$$

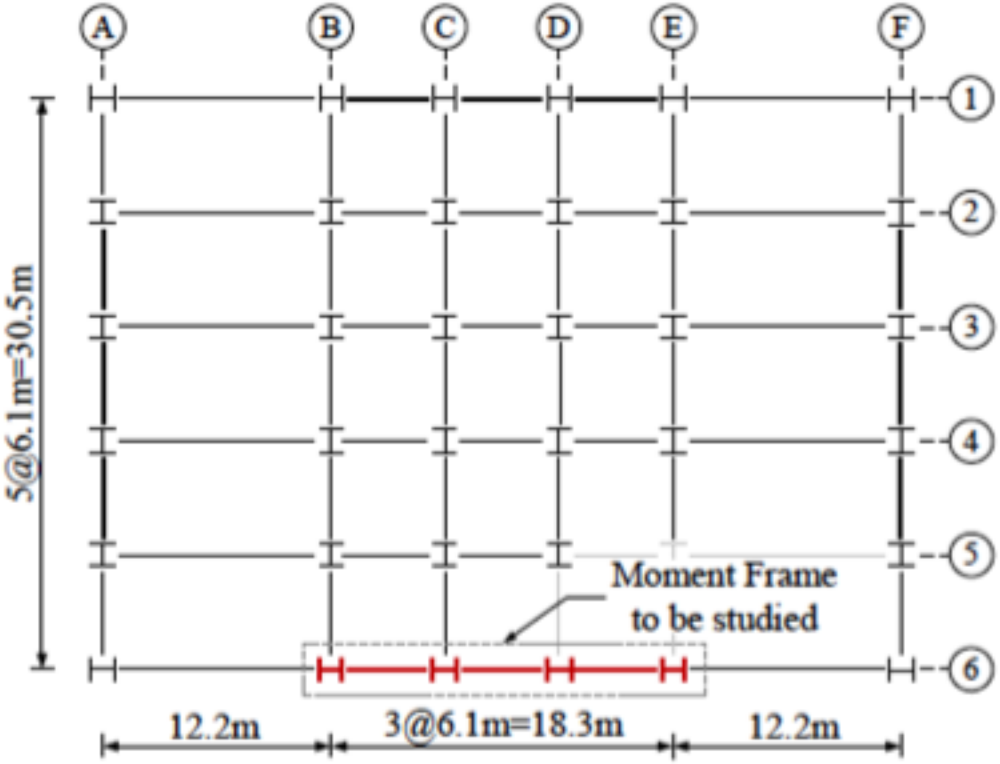
- $E\left[L_T \middle| IM\right]$: Expected total repair costs conditioned on seismic intensity *IM*.
- $P\left(NC \cap R \middle| IM\right)$: Probability of having no-collapse given *IM*
- $P\left(NC \cap D \middle| IM\right)$: Probability of having no-collapse given *IM* but the building will be demolished.
- $P\left(C \middle| IM\right)$: Probability of having collapse given *IM*.
- Probability of demolition given IM but no collapse (Assumed μ=1.5% and σ=0.30) :

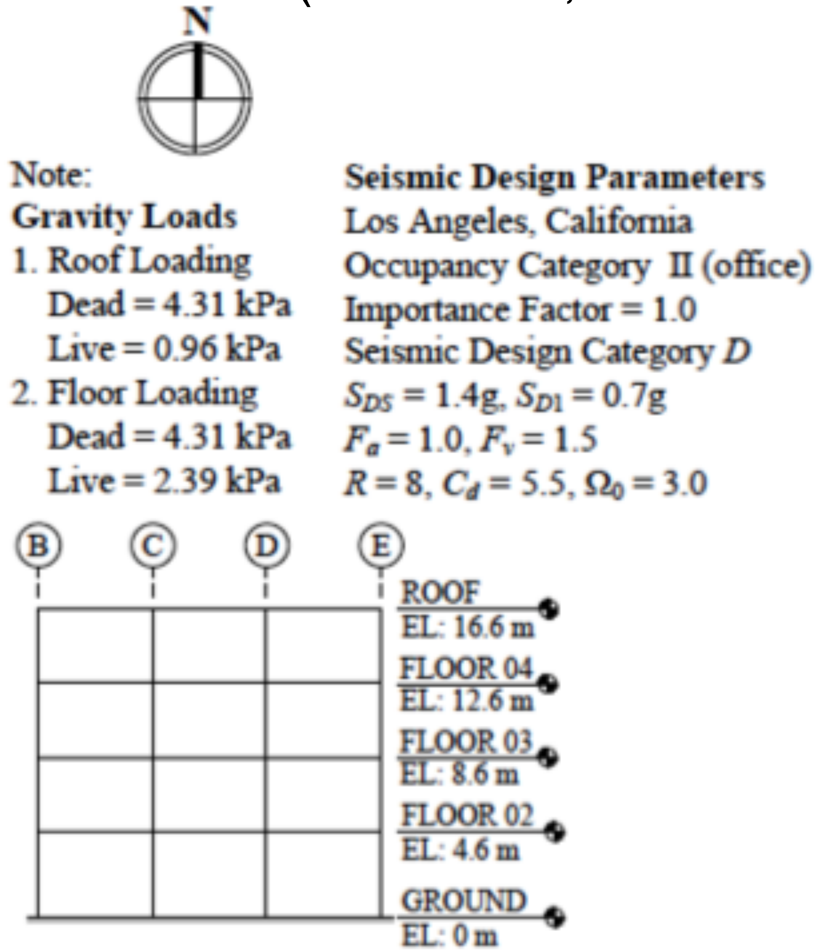
$$P\left(D \middle| NC, IM\right) = \int_0^\infty P\left(D \middle| RSDR\right) dP\left(RSDR \middle| NC, IM\right)$$

Source: Ramirez and Miranda (2013)

Example: Steel Frame Buildings with MRFs

Archetype office steel buildings (2- to 20-stories) with perimeter steel special moment frames designed in Urban California (IBC 2009, AISC-2010)



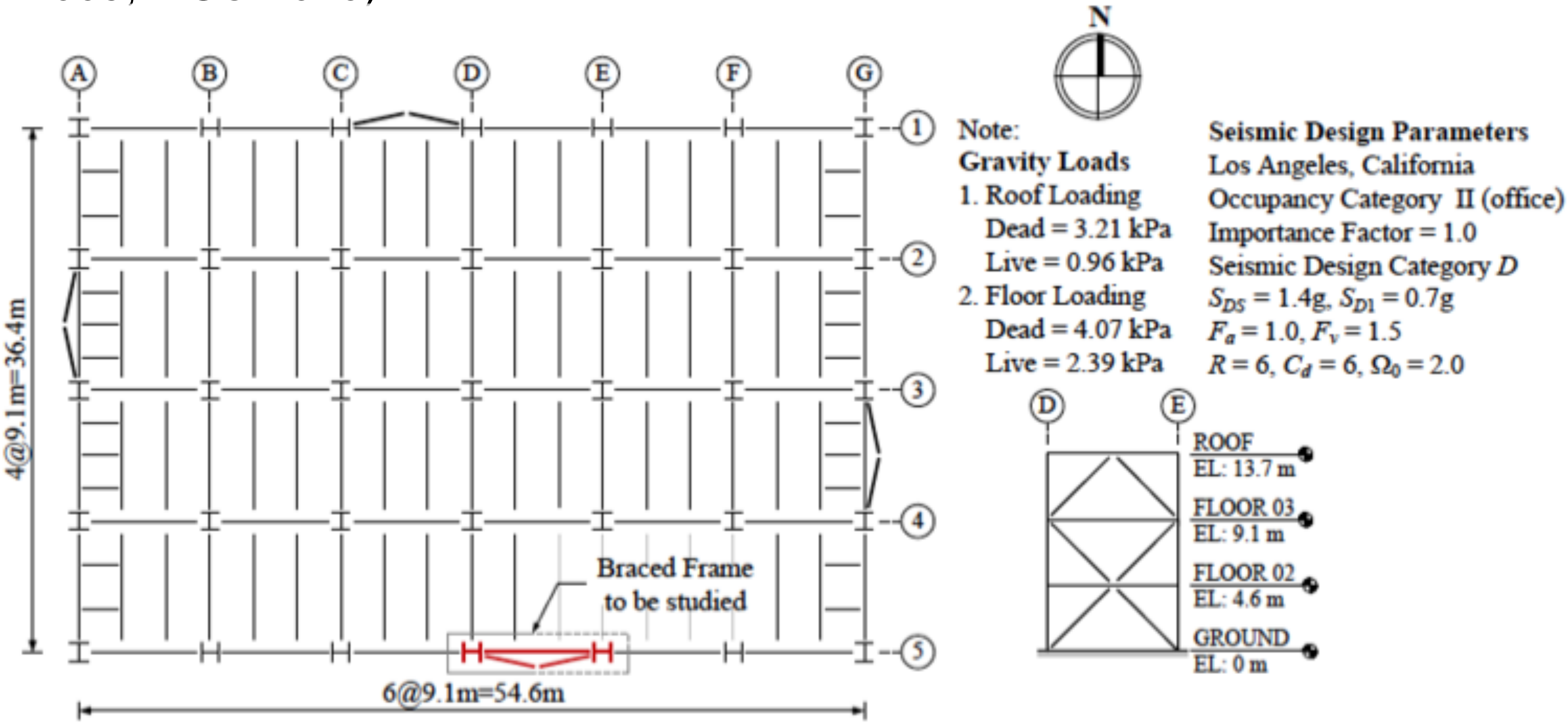


(Sources: Elkady and Lignos 2014*)

*Elkady, A. and Lignos, D.G. (2014). "*Modeling of the Composite Action in Fully Restrained Beam-to-Column Connections: Implications in the Seismic Design and Collapse Capacity of Steel Special Moment Frames*". Earthquake Engineering and Structural Dynamics (EESD). Vol. 43(13), pp. 1935-1954, DOI: 10.1002/eqe.2430.

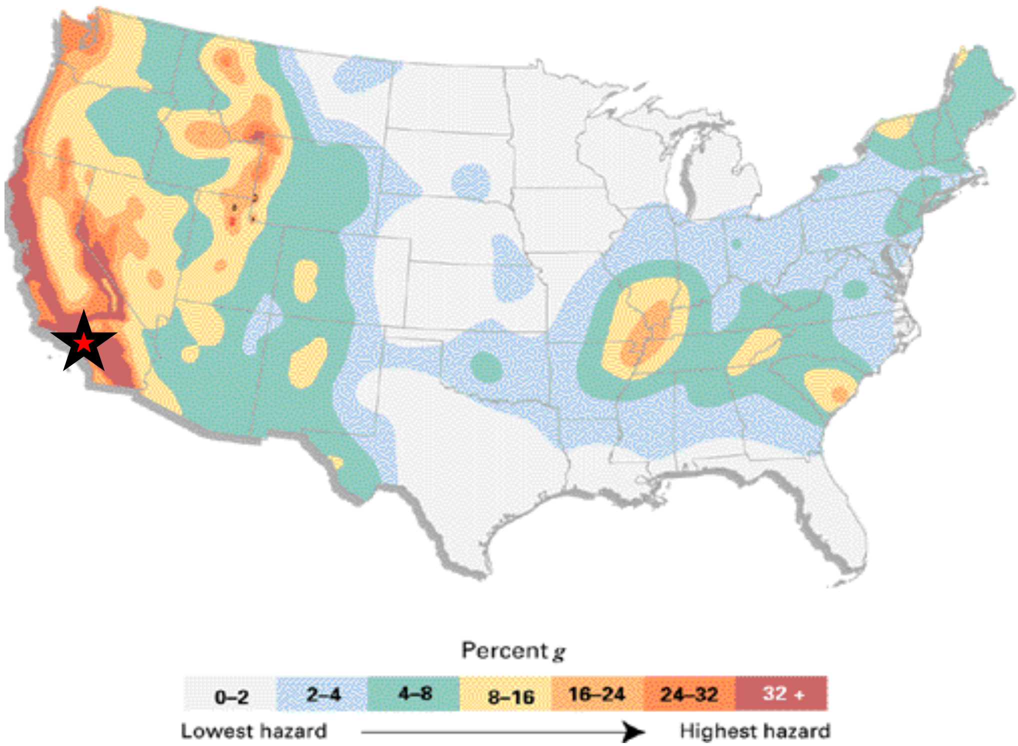
Steel Frame Buildings with Concentrically Braced Frames

Archetype office steel buildings (2- to 12-stories) with perimeter steel special concentrically braced frames designed in Urban California (IBC 2009, AISC-2010)

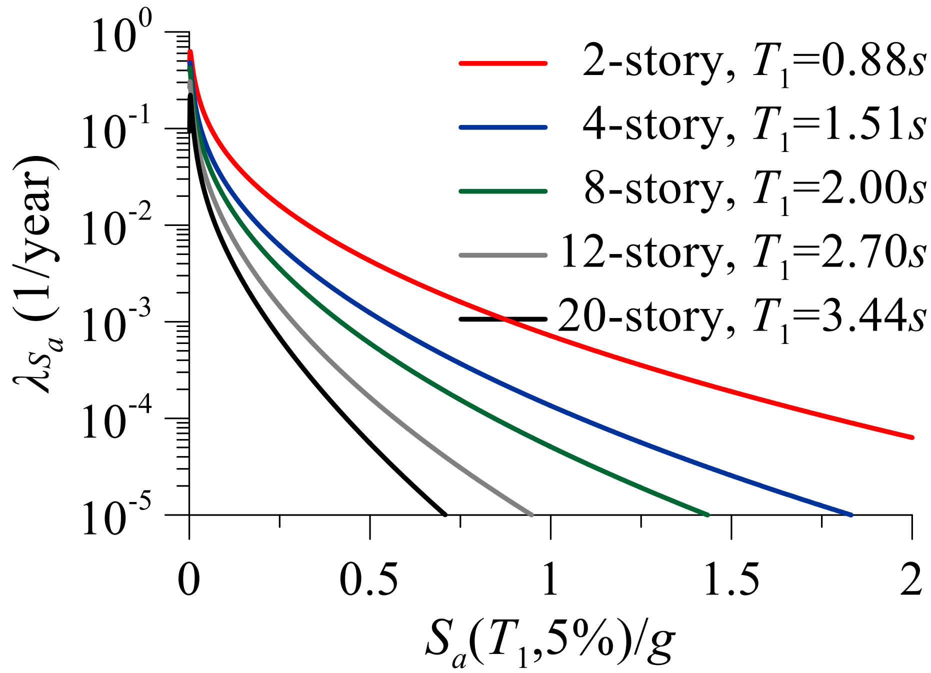


(Sources: NIST 2010)

Seismic Hazard in Design Location of Interest



Source: National Seismic Hazard Map (USGS 2008)



Fragility and Cost Distribution Functions

- ✧ To compute realistic loss estimations for steel frame buildings architectural layouts were developed.
- ✧ Steel frame buildings with SMFs: rectangular footprint of 14,000 ft^2
- ✧ Cost estimates were developed based on the RS Means Cost Estimating Manuals.
- ✧ Non-structural components (both drift- and acceleration-sensitive) were considered to compute the replacement cost estimates per building.
- ✧ Structural components (e.g., beam-to-column connections, columns, slabs, base plates, etc) were also considered.
- ✧ Base case replacement cost was estimated to be \$250/ft^2.

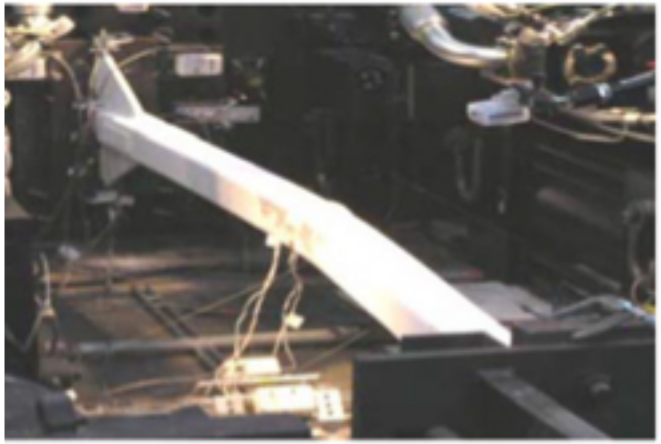
Fragility and Cost Distribution Functions (3)

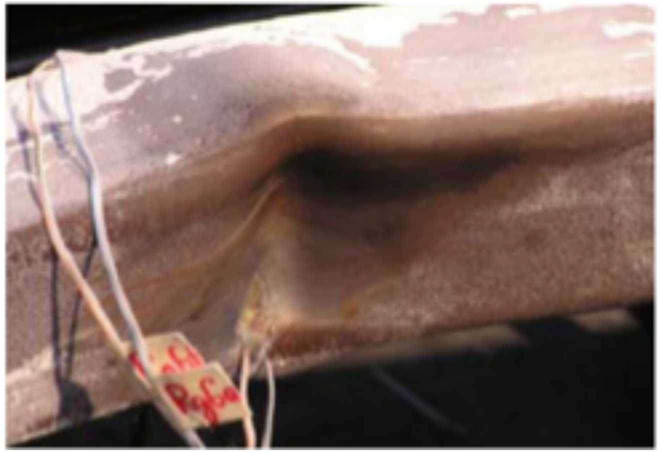
-Examples of Damageable Components

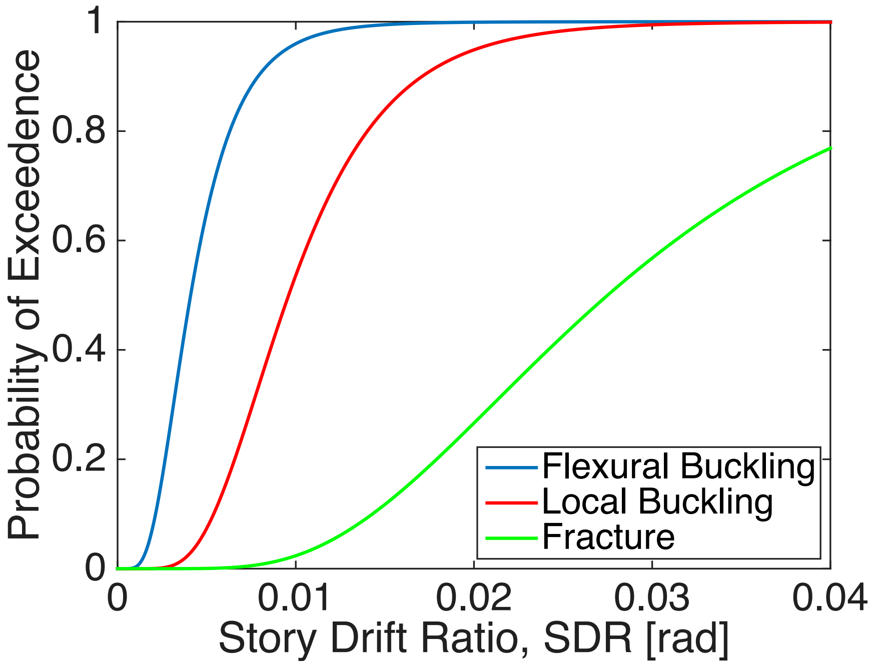
Assembly description	Damage state	Unit	Fragility parameters			Repair cost parameters	
			EDP	x_m	β	x_m ($)	β
Columns base	Crack initiation	EA	SDR	0.04	0.40	19224	0.41
(W < 223kg/m) [7, 8]	Crack propagation	EA		0.07	0.40	27263	0.37
	Fracture	EA		0.10	0.40	32423	0.34
Columns base	Crack initiation	EA	SDR	0.04	0.40	20082	0.39
(223kg/m < W < 446kg/m)	Crack propagation	EA		0.07	0.40	29395	0.34
[7, 8]	Fracture	EA		0.10	0.40	36657	0.31
Columns base	Crack initiation	EA	SDR	0.04	0.40	21363	0.37
(W > 446kg/m) [7, 8]	Crack propagation	EA		0.07	0.40	32567	0.31
	Fracture	EA		0.10	0.40	41890	0.27
Column splices	Crack Initiation	EA	SDR	0.04	0.40	9446	0.32
(W < 446kg/m) [7, 8]	Crack Propagation	EA		0.07	0.40	11246	0.30
	Fracture	EA		0.10	0.40	38473	0.17
Column splices	Crack Initiation	EA	SDR	0.04	0.40	10246	0.30
(223kg/m < W < 446kg/m)	Crack Propagation	EA		0.07	0.40	13012	0.27
[7, 8]	Fracture	EA		0.10	0.40	42533	0.16
Column splices	Crack Initiation	EA	SDR	0.04	0.40	11446	0.27
(W > 446kg/m) [7, 8]	Crack Propagation	EA		0.07	0.40	14812	0.24
	Fracture	EA		0.10	0.40	47594	0.14
Column (≤ W27) [7, 8]	Local buckling	EA	SDR	0.03	0.30	16033	0.35
	Lateral-torsional buckling	EA		0.04	0.30	25933	0.31
	Fracture	EA		0.05	0.30	25933	0.31
Column (≥ W30) [7, 8]	Local buckling.	EA	SDR	0.03	0.30	17033	0.33
	Lateral-torsional buckling	EA		0.04	0.30	28433	0.28
	Fracture	EA		0.05	0.30	28433	0.28
RBS moment connections	Yield anywhere	EA	SDR	0.01	0.17	0	0
(one-sided, ≤ W27) [38]	Local buckling	EA		0.0216	0.30	16033	0.35
	Fracture	EA		0.05	0.30	25933	0.31

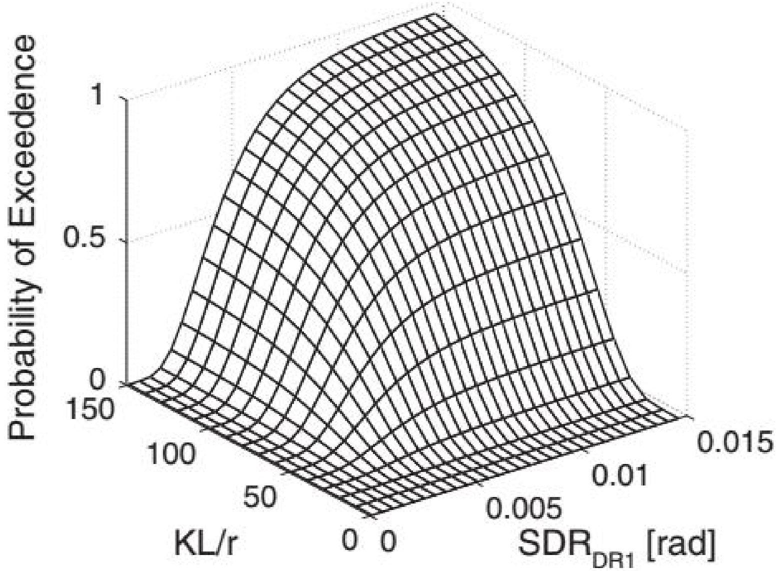
Fragility and Cost Distribution Functions (2)

-Examples of Damageable Components and Damage States







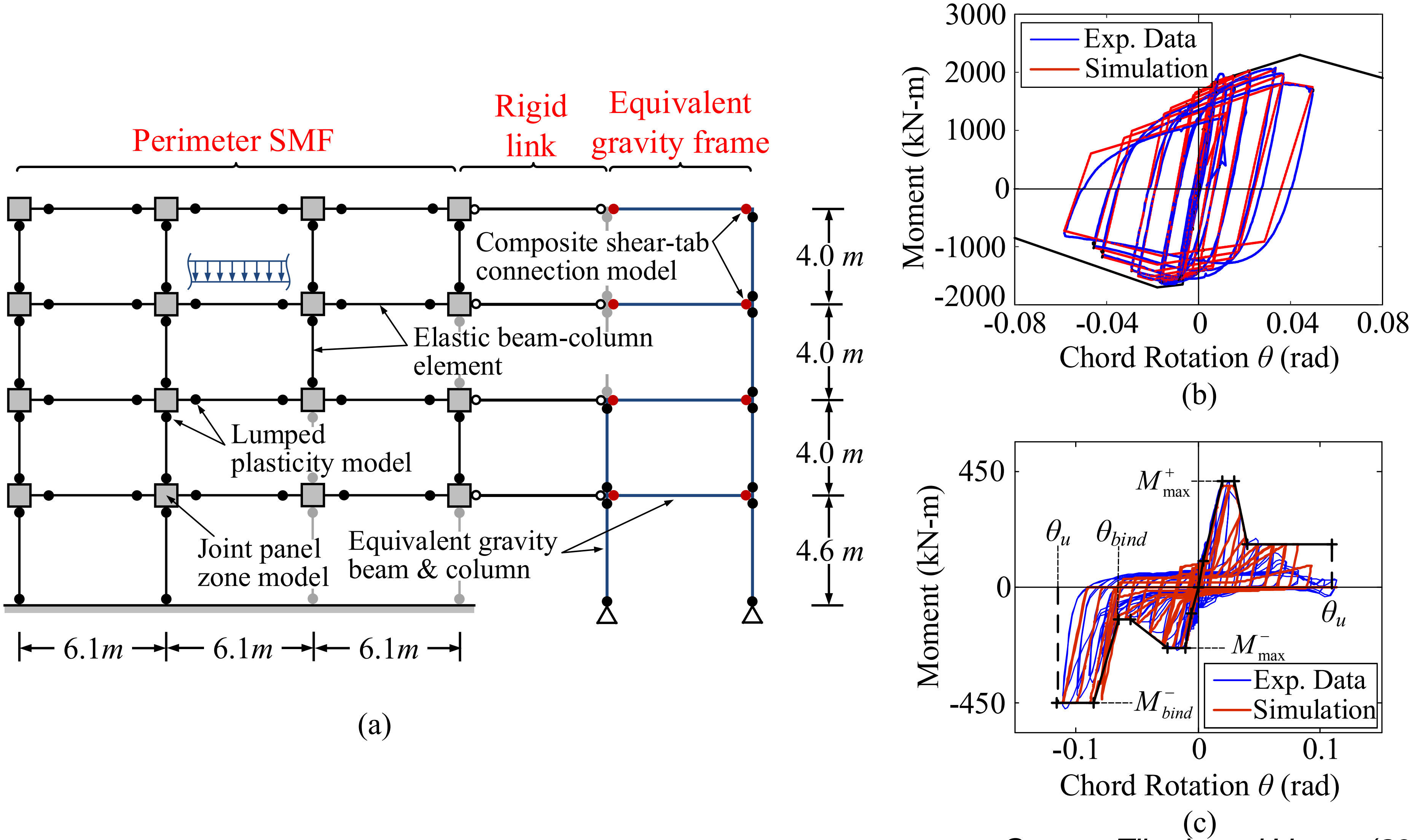


(Source: Lignos and Karamanci 2013*)

*Lignos, D.G., and Karamanci, E. (2013). "Drift-based and Dual-Parameter Fragility Curves for Concentrically Braced Frames in Seismic Regions". Journal of Construnctional Steel Research, Vol. 90, pp. 209-220.

Steel Frame Buildings with Moment Resisting Frames

-Modeling of Composite Action and Interior Gravity Framing



*Source: Elkady and Lignos (2014)**

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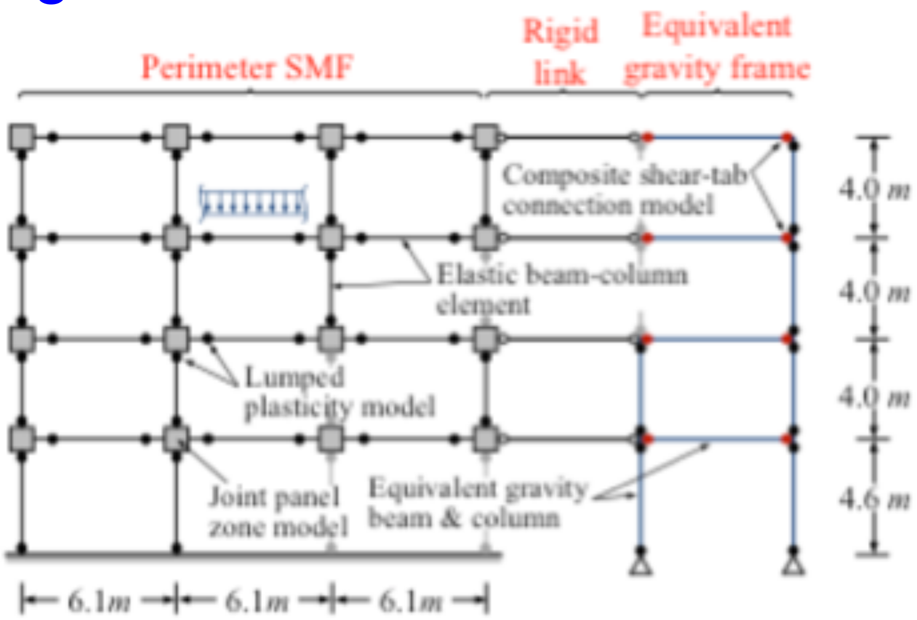
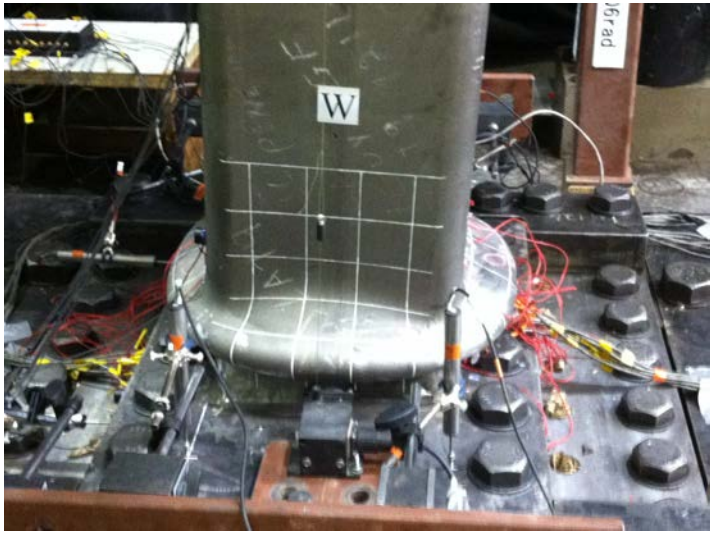
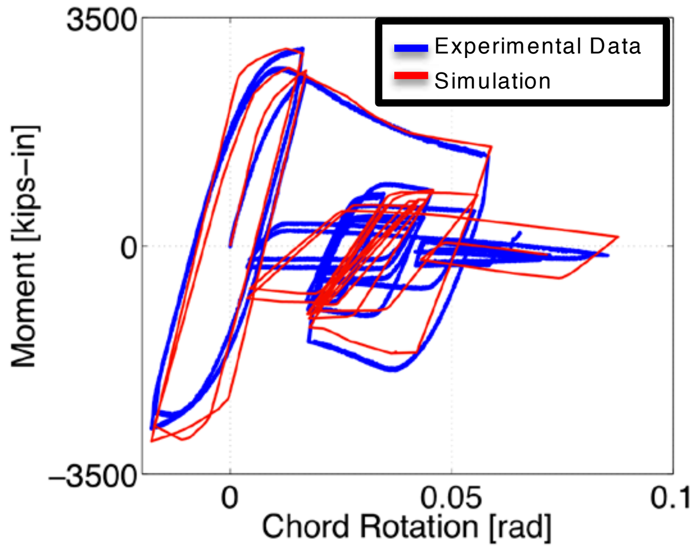
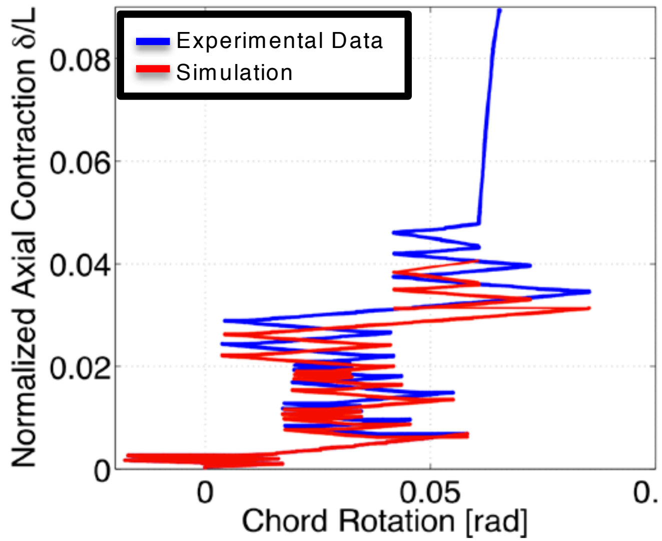
Steel Frame Buildings with Moment-Resisting Frames

-Modeling of steel columns







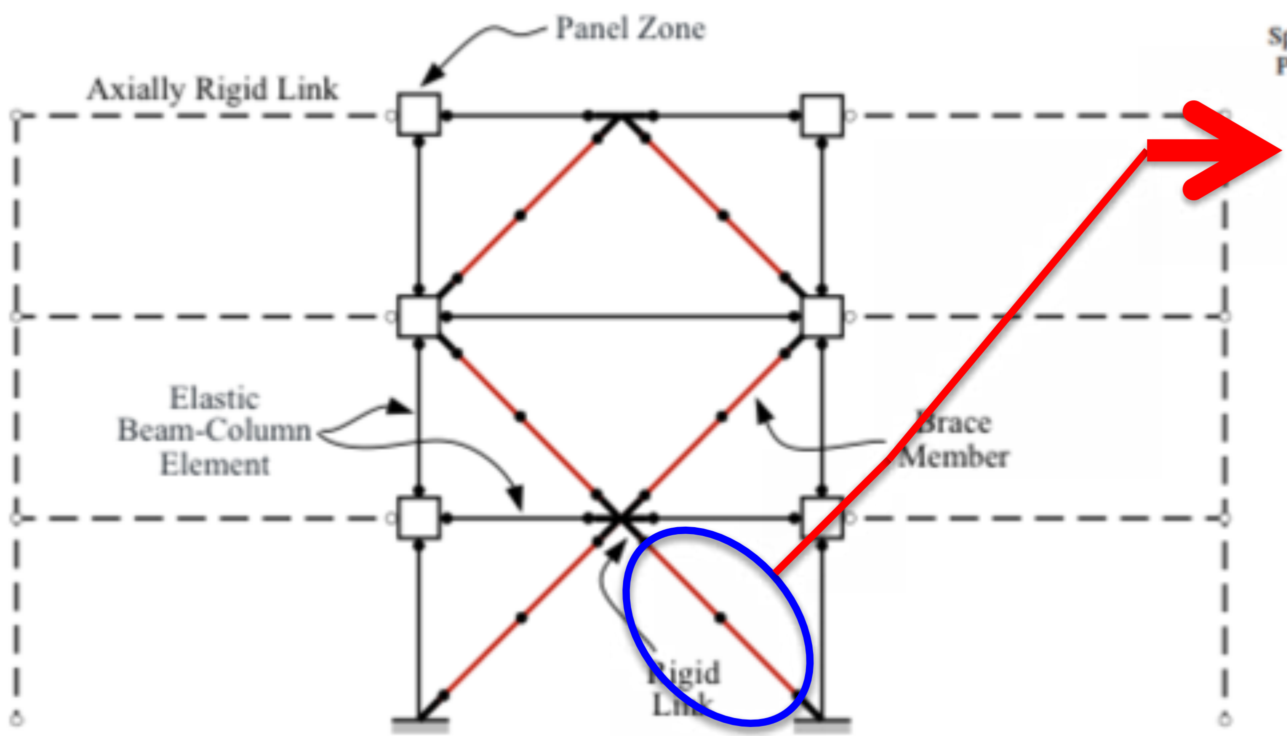


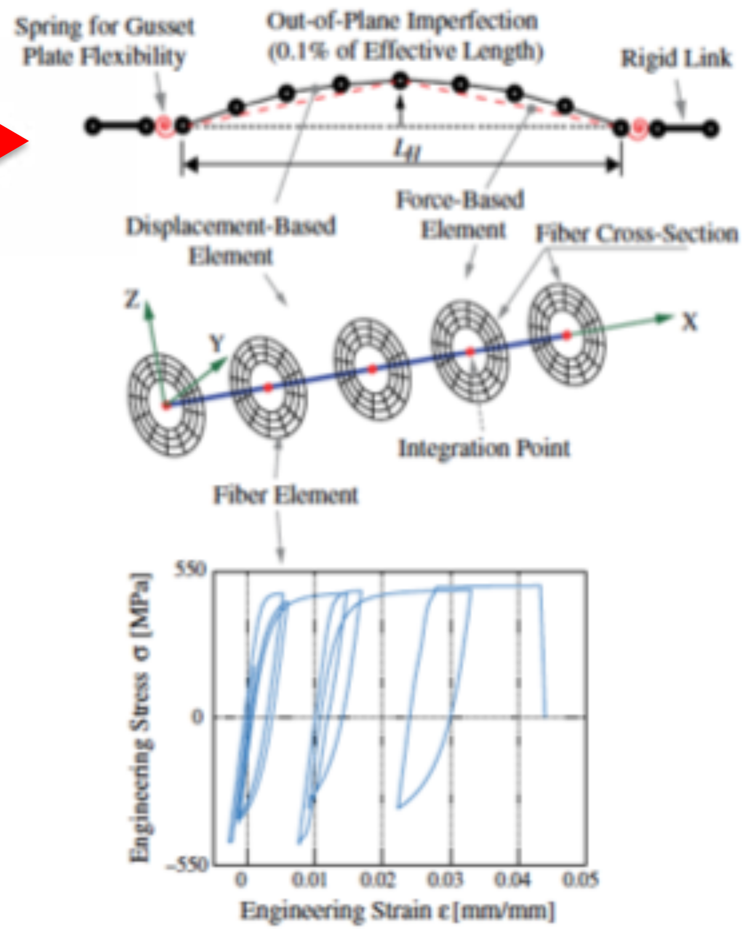
*Source: Suzuki and Lignos (2015)**

*Suzuki, Y., Lignos, D.G. (2015). "*Large Scale Collapse Experiments of Wide Flange Steel Beam-Columns*", Proceedings 8th International Conference on Behavior of Steel Structures in Seismic Areas, Shanghai, China, July 1-3, 2015.

Steel Frame Buildings with Special Concentrically Braced Frames

-Modeling of Steel Braces: Flexural Buckling and Fracture due to Low-Cycle Fatigue





Calibrated with over 270 tests from steel braces

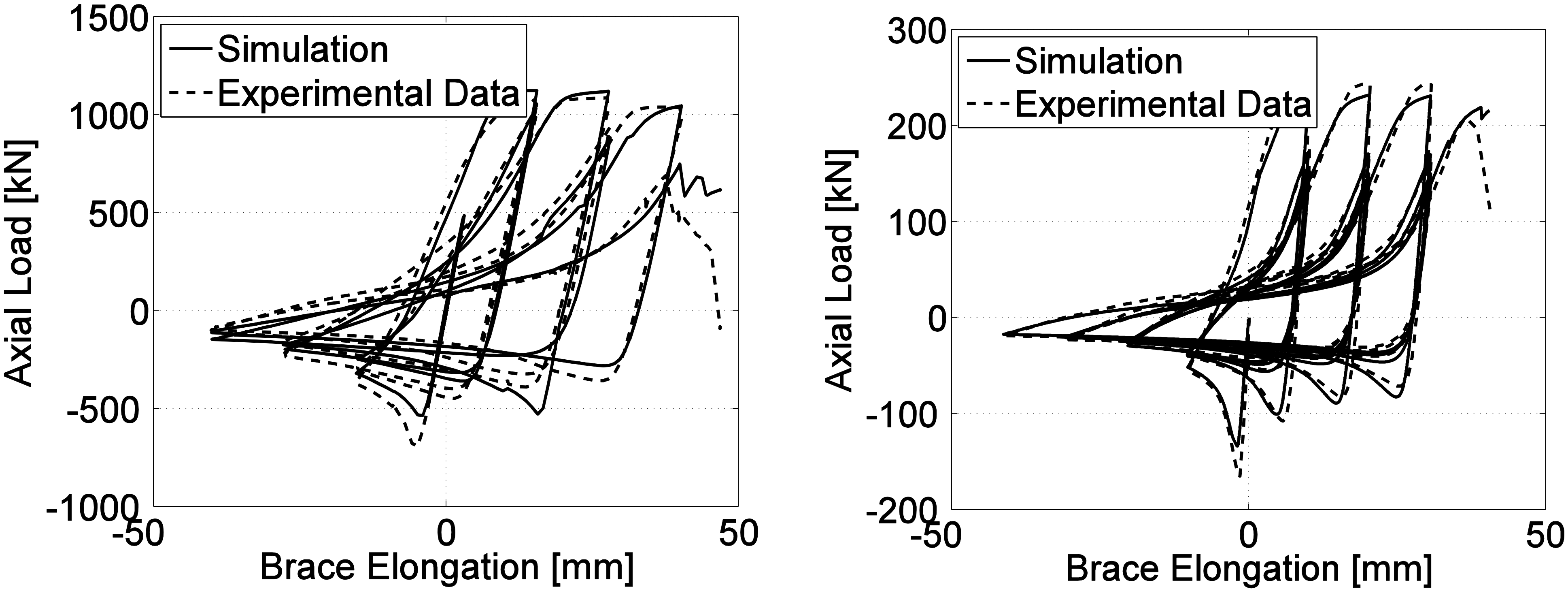
$$\varepsilon_0 = 0.748\left(\frac{kL}{r}\right)^{-0.399}\left(\frac{D}{t}\right)^{-0.628}\left(\frac{E}{F_y}\right)^{0.2}$$

*Source: Karamanci and Lignos (2014)**

*Karamanci, E., and Lignos, D.G. (2014). "*Computational Approach for Collapse Assessment of Concentrically Braced Frames in Seismic Regions.*" ASCE, Journal of Structural Engineering, Vol. 15(A401419), pp. 1-15.

Steel Frame Buildings with Special Concentrically Braced Frames

-Modeling of Steel Braces: Flexural Buckling and Fracture due to Low-Cycle Fatigue



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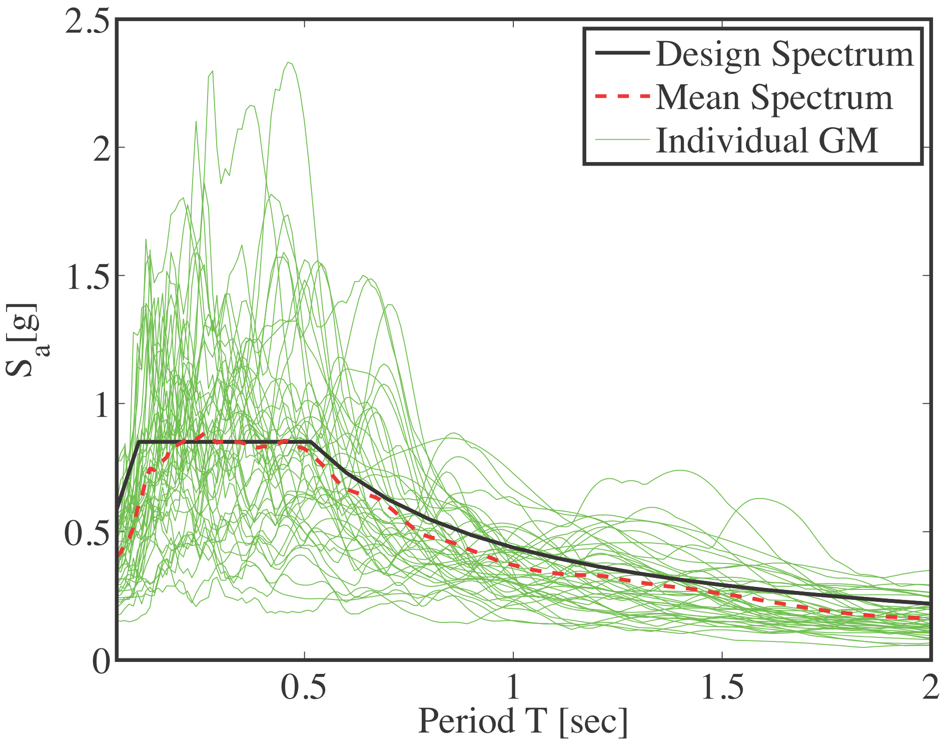
Tracing Sidesway Collapse of Frame Buildings

-Example of definition of dynamic collapse due to earthquake shaking

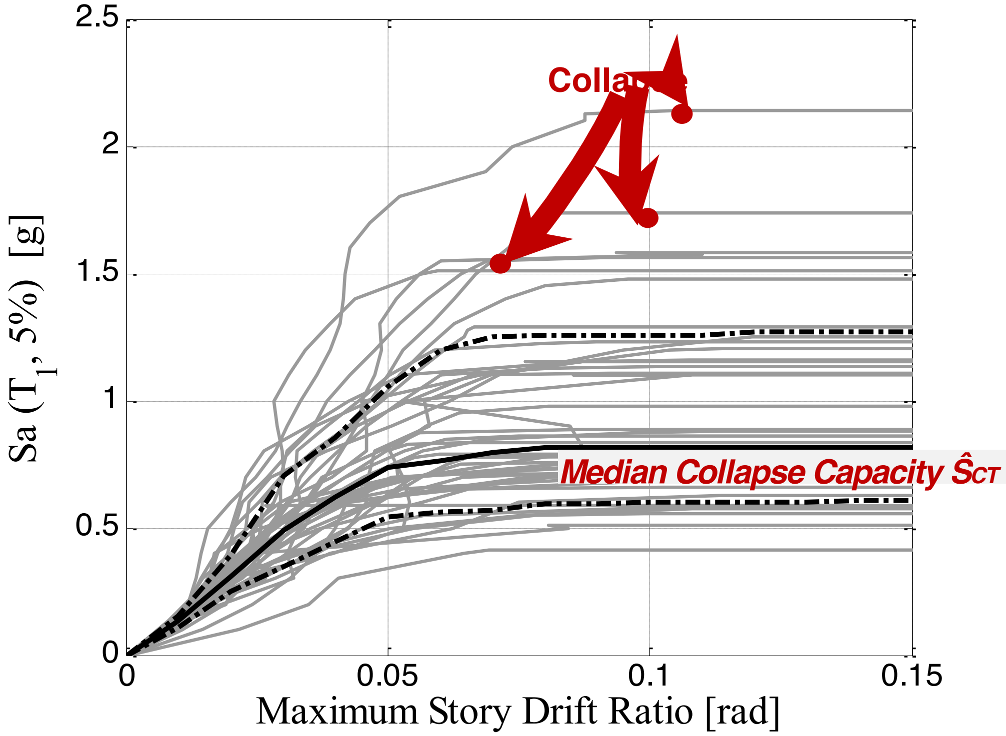
Collapse Risk of Steel Frame Buildings with MRFs

-Ground Motion Sets and Process to Trace Collapse

Ground Motion Set from FEMA P695
Far-Field Set of 44 Ground Motions



Incremental Dynamic Analysis
to Trace Dynamic Instability



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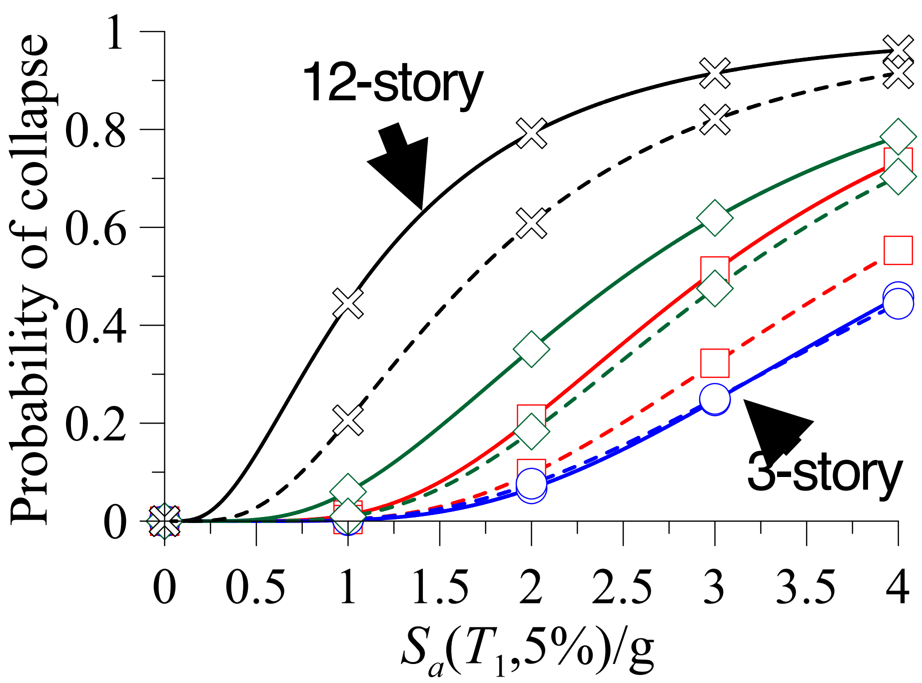
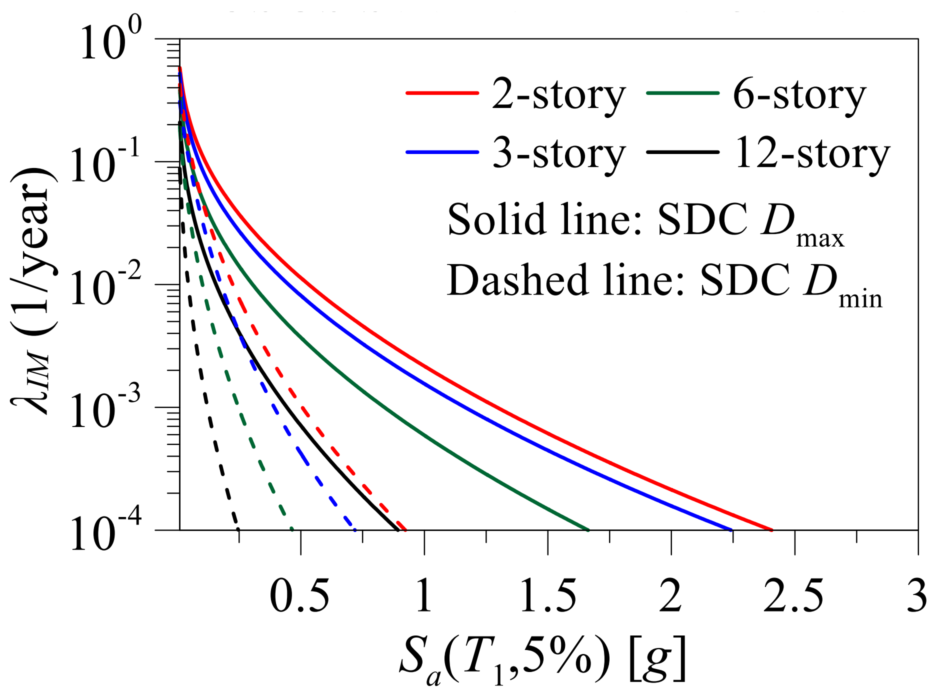
Evaluating the Collapse Risk of Steel Structures

-**Collapse Metric**: Mean Annual Frequency of Collapse, *λc*





$$\lambda_c = \int_0^{\infty} \left(P_c | Sa\right) \cdot \left| \frac{d\lambda_{Sa}(Sa)}{d(Sa)} \right| d(Sa)$$

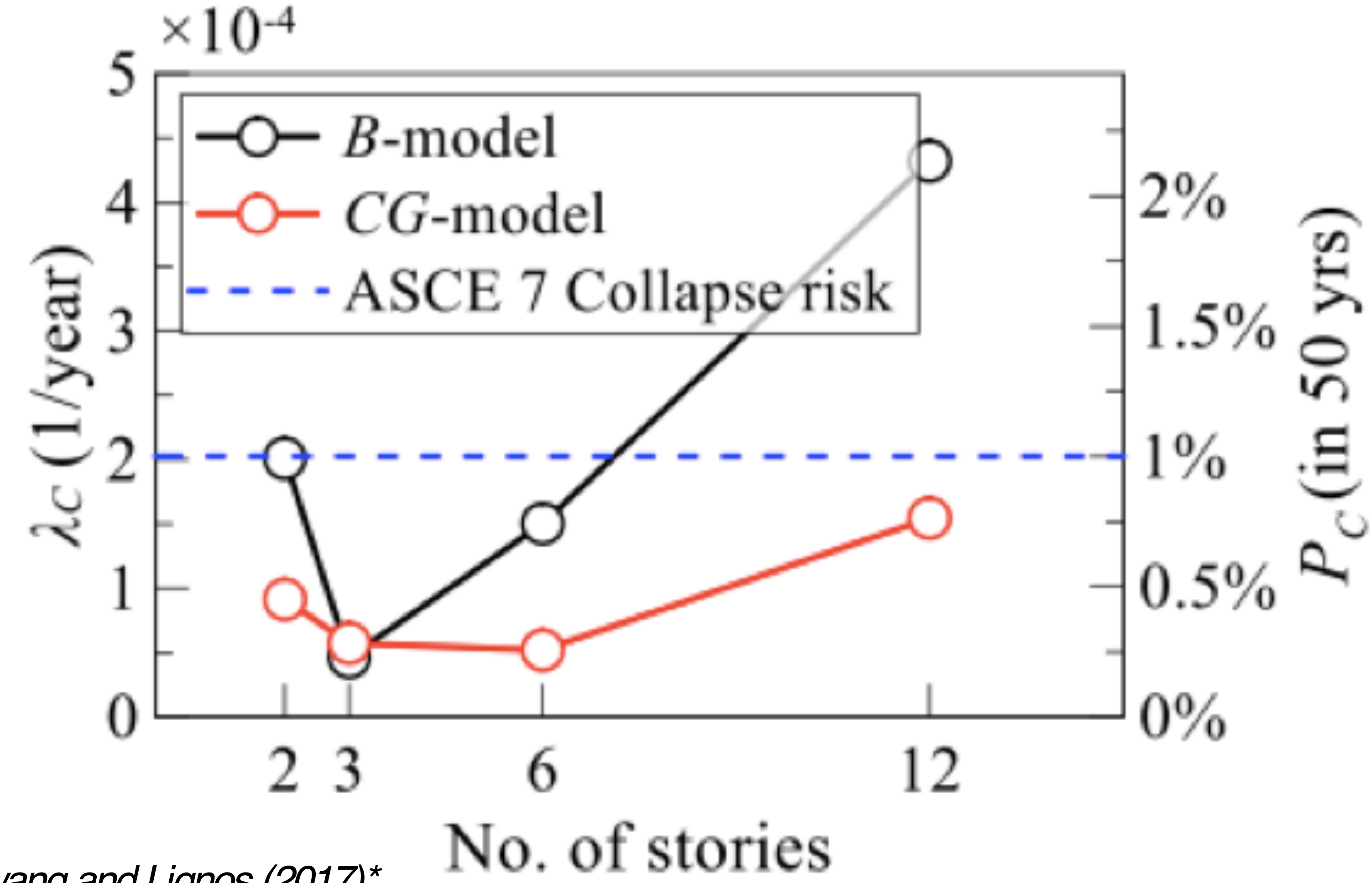
$$P_{collapse}(in\ t\ years) = 1 - \exp(-\lambda_c t)$$

(e.g., assume building life expectancy *t*=50years)

*Source: Eads et al. (2013)**

*Eads, L., Miranda, E., Krawinkler, H., Lignos, D.G. (2013). "*An Efficient Method for Estimating the Collapse Risk of Structures in Seismic Regions*". Earthquake Engineering and Structural Dynamics (EESD), Vol. 42(1), pp. 25-41, DOI: 10.1002/eqe.2191.

Collapse Risk of Steel Frame Buildings with Concentrically Braced Frames

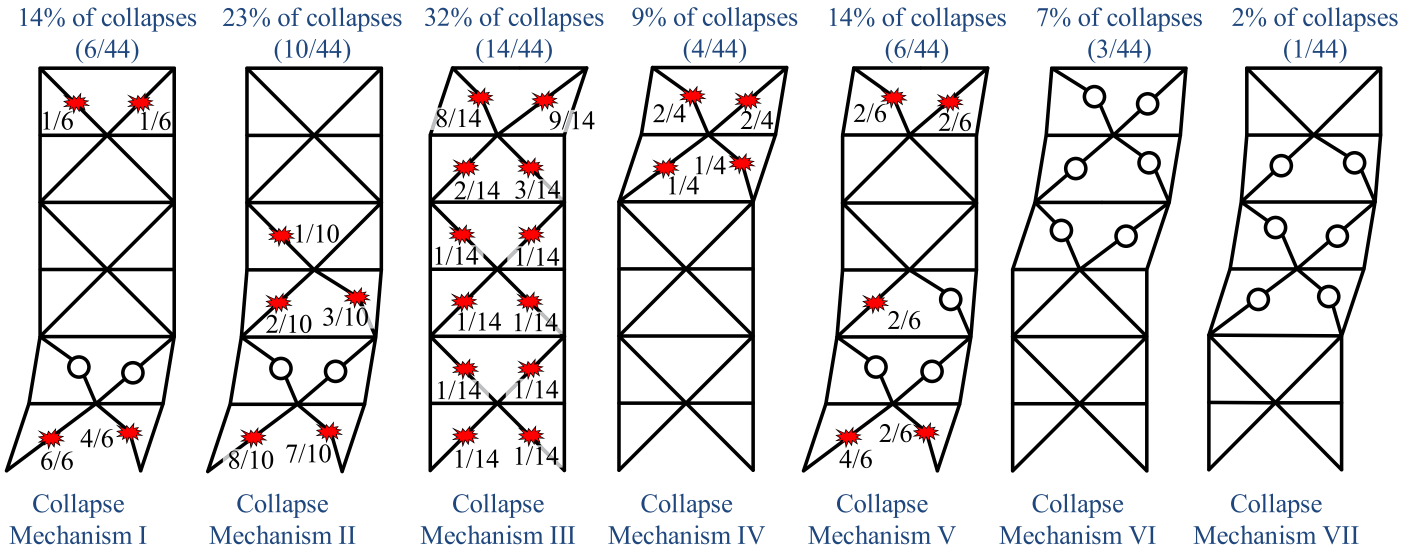


*Source: Hwang and Lignos (2017)**

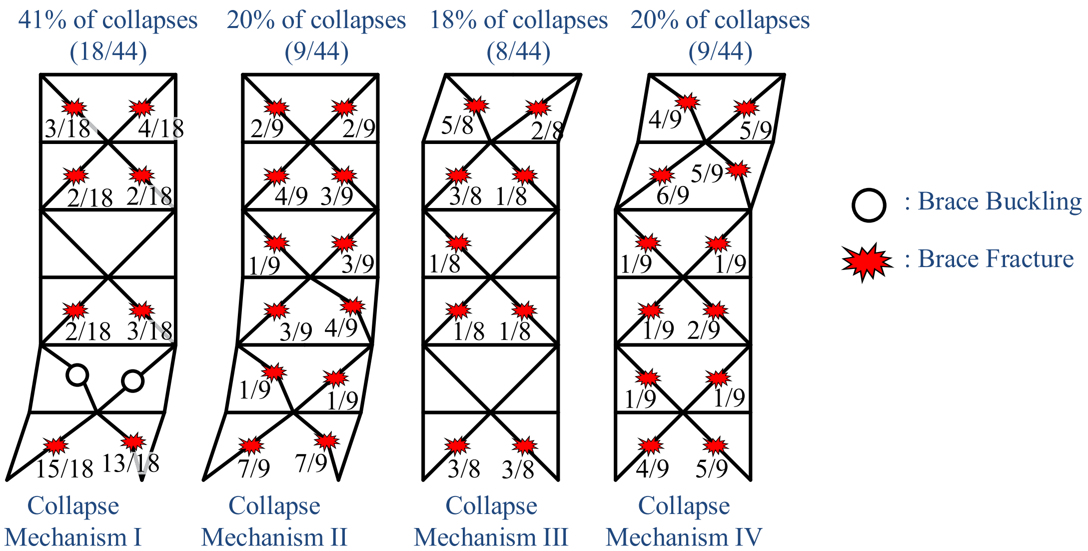
*Hwang, S-H., Lignos, D.G. (2017). "**Effect of Modeling Assumptions on the Earthquake-Induced Losses and Collapse Risk of Steel-Frame Buildings with Special Concentrically Braced Frames**; *ASCE Journal of Structural Engineering*. Vol. 143(9), DOI : 10.1061/(ASCE)ST.1943-541X.0001851.

Collapse Mechanisms of steel CBFs

Bare Frame Models



Models with Gravity Framing



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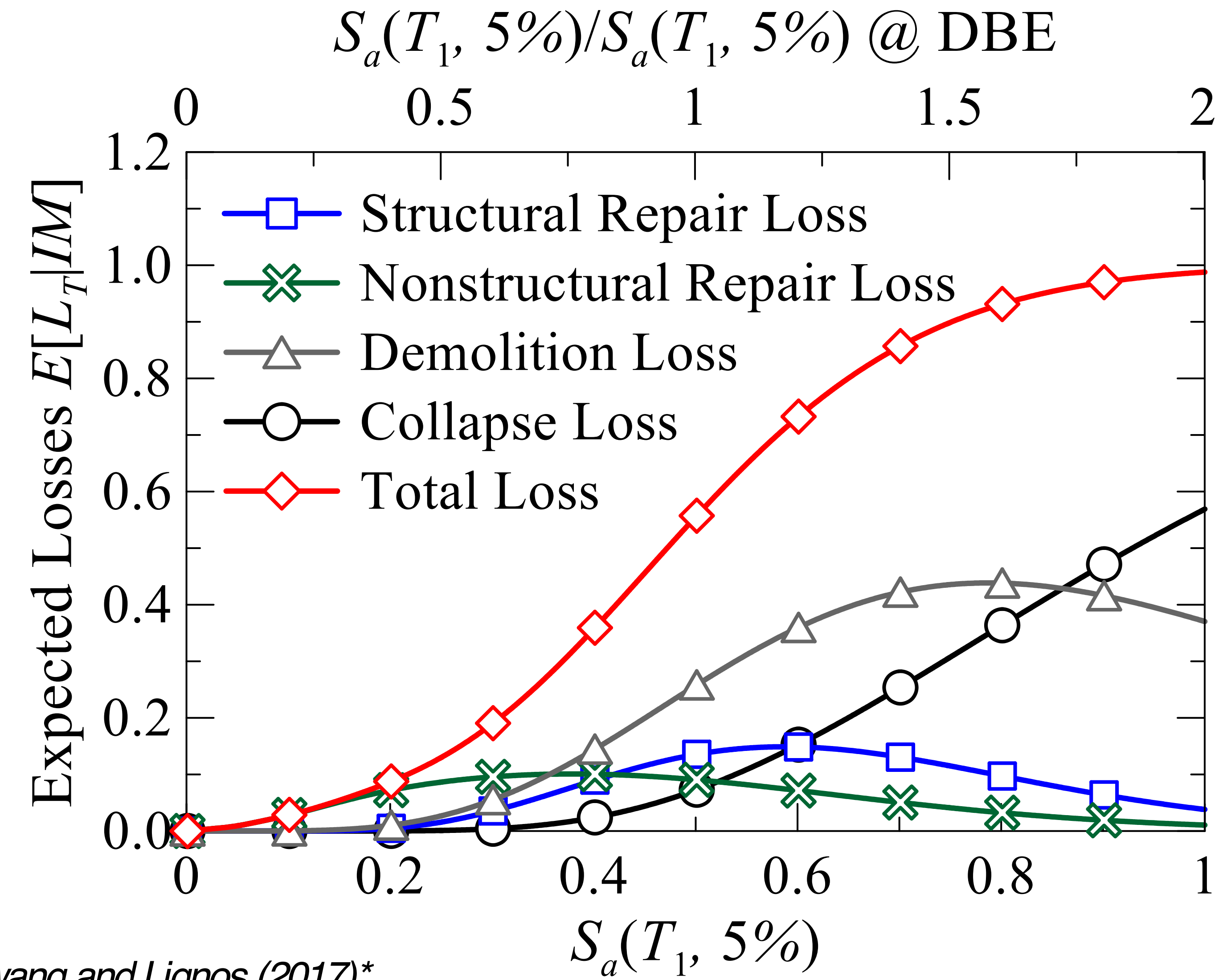
Normalized Loss Vulnerability Functions

-Utilization of Bare Frame Analytical Models



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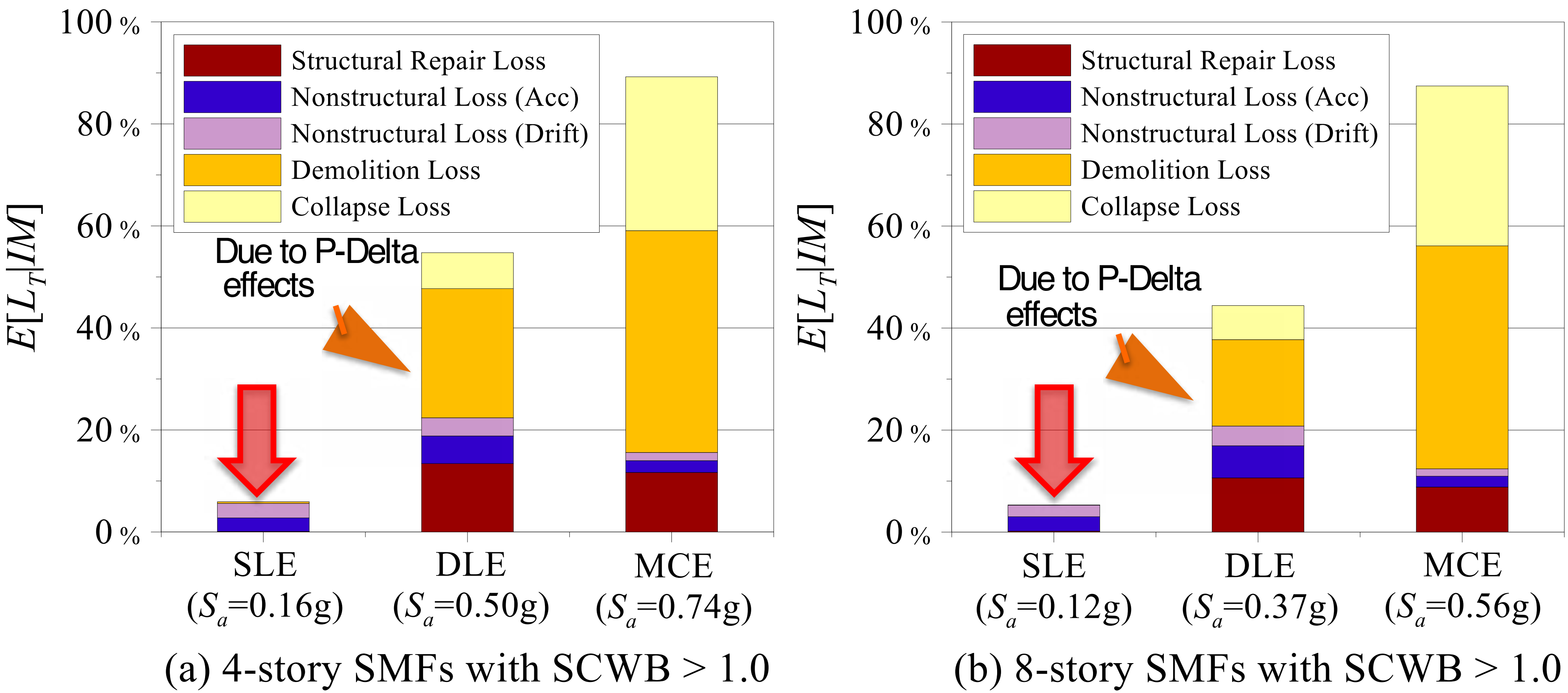
Expected Losses Conditioned on Seismic Intensity

-Utilization of Bare Frame Analytical Models

- ✧ Hazards: Service Level, Design Basis (DLE) & Maximum Considered Event (MCE)
- ✧ Minimum monetary loss due to business interruption is not considered



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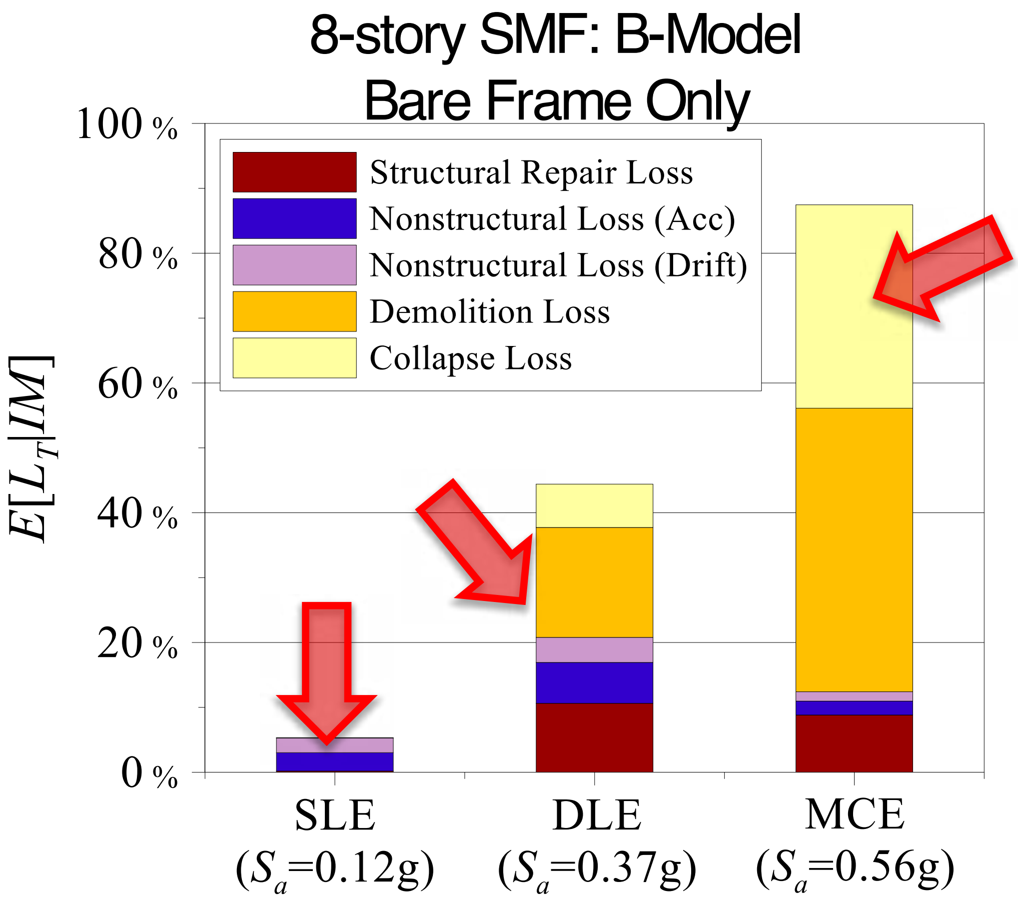
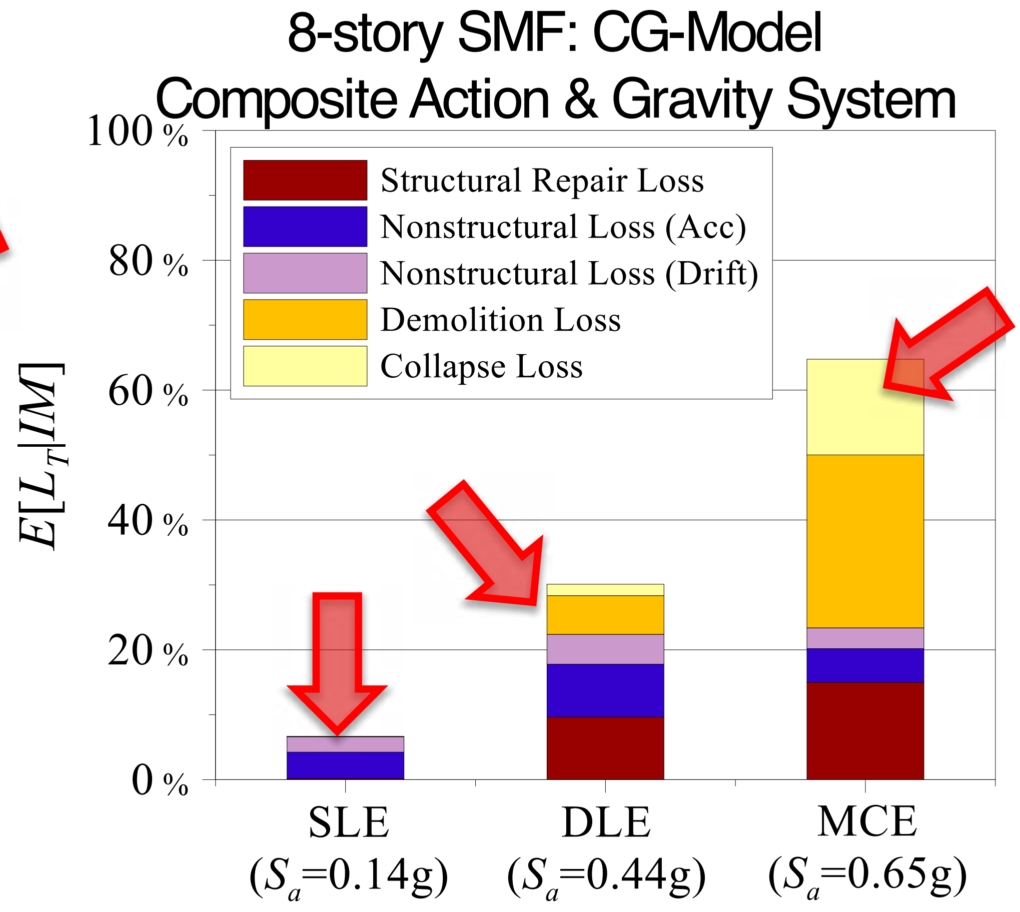
Expected Losses Conditioned on Seismic Intensity

-Effect of Analytical Model Representation: Steel MRFs



(a) 8-story SMFs with SCWB > 1.0



(b) 8-story SMFs with SCWB > 1.0

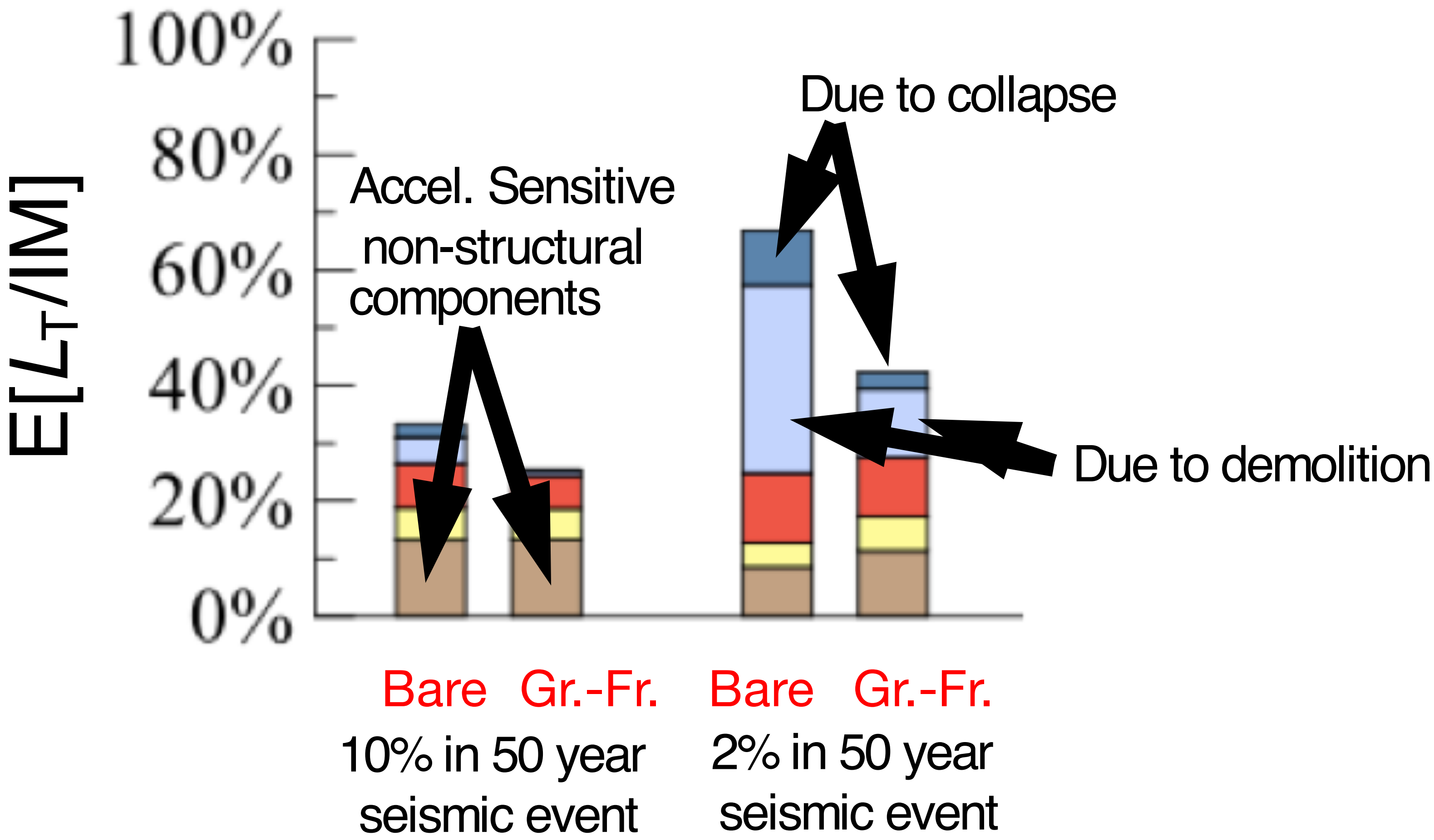
Earthquake-induced loss assessment at discrete levels of intensity may be over-conservative when it is based on “bare frame” model representations of the building.

*Hwang, S-H., Lignos, D.G. (2017). “Earthquake-induced loss assessment of steel frame buildings with special moment frames designed in highly seismic regions, *Earthquake Engineering and Structural Dynamics (EESD), Vol. 46(13),* 2141–2162. doi:10.1002/eqe.2898.

Expected Losses Conditioned on a Single Seismic Intensity

-Effect of Numerical Model Representation on Losses

Illustration: 6-story Steel Frame Building with CBFs



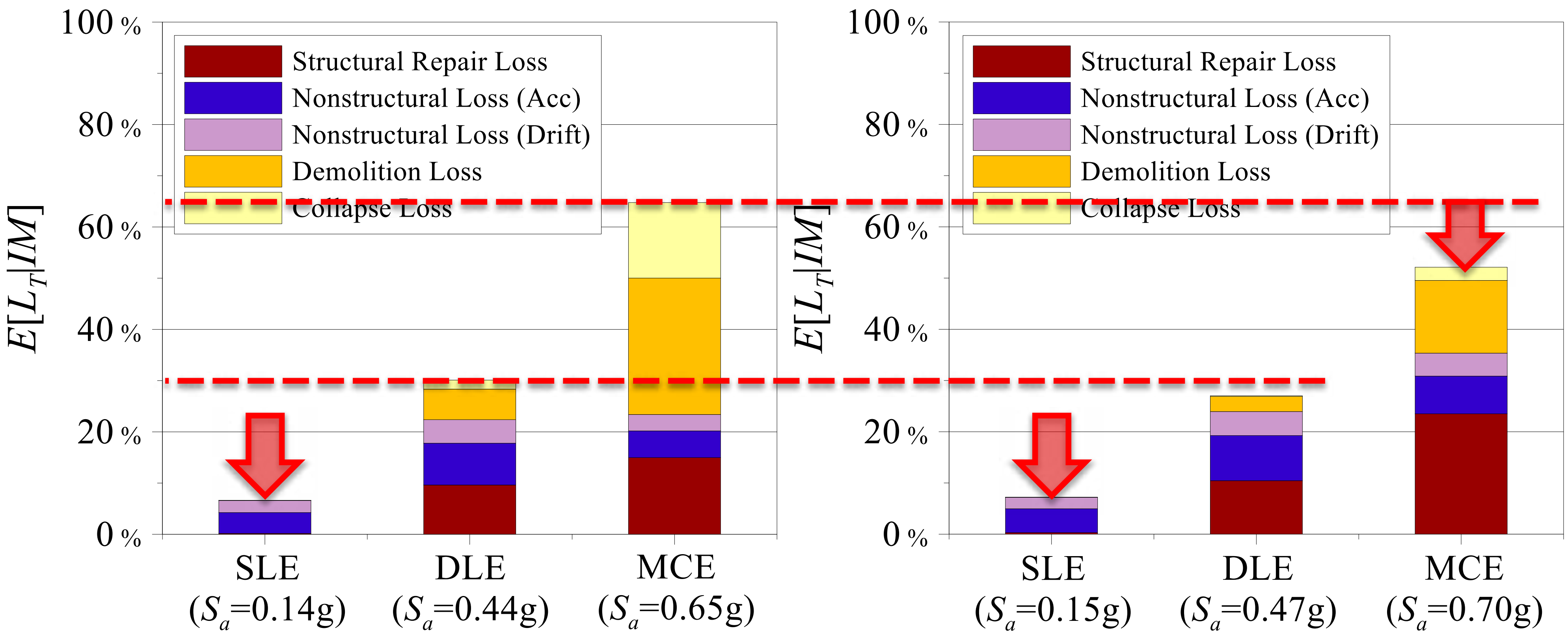
*Source: Hwang and Lignos (2017)**

*Hwang, S-H., Lignos, D.G. (2017). "Earthquake-induced loss assessment of steel frame buildings with special moment frames designed in highly seismic regions, *Earthquake Engineering and Structural Dynamics (EESD), Vol. 46(13),* 2141–2162. doi:10.1002/eqe.2898.

Expected Losses Conditioned on Seismic Intensity

Effect of Strong-Column-Weak-Beam Ratio on Expected Losses

- ✧ Hazards: Service Level, Design Basis (DLE) & Maximum Considered Event (MCE)
- ✧ Minimum monetary loss due to business interruption is not considered



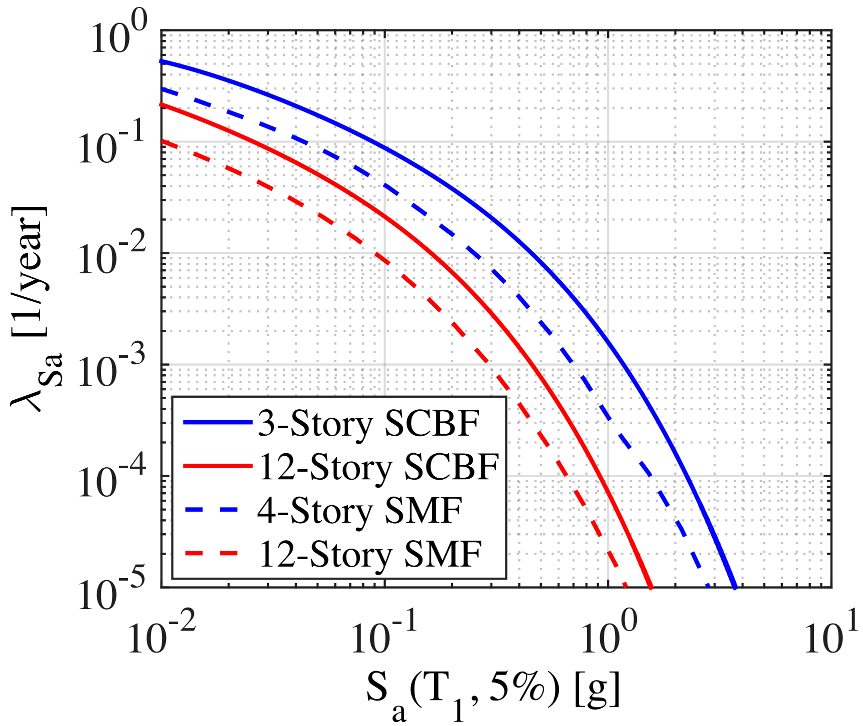
(a) 8-story SMFs with SCWB > 1.0 (b) 8-story SMFs with SCWB > 2.0

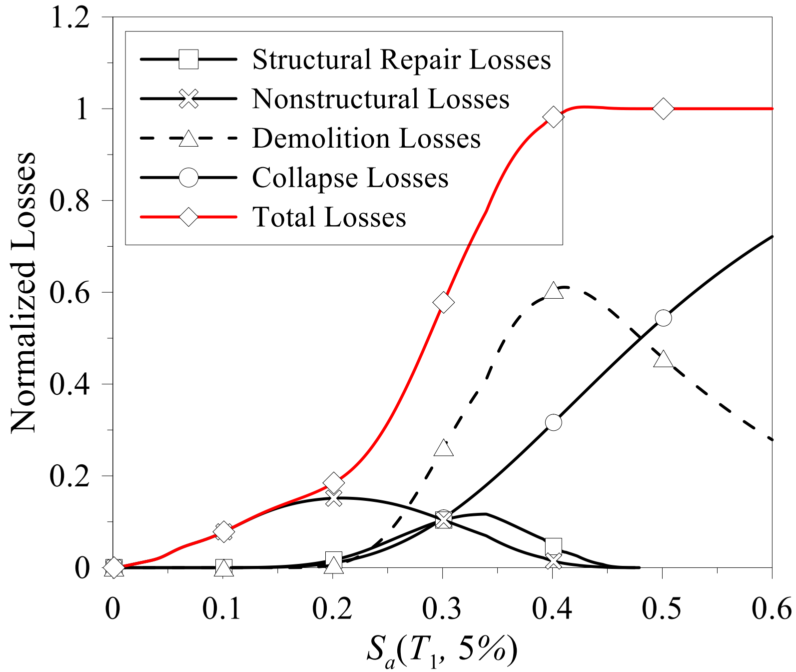
*Hwang, S-H., Lignos, D.G. (2017). "Earthquake-induced loss assessment of steel frame buildings with special moment frames designed in highly seismic regions, *Earthquake Engineering and Structural Dynamics (EESD), Vol. 46(13),* 2141–2162. doi:10.1002/eqe.2898.

Expected Annual Losses (*EAL*) as a Loss Metric

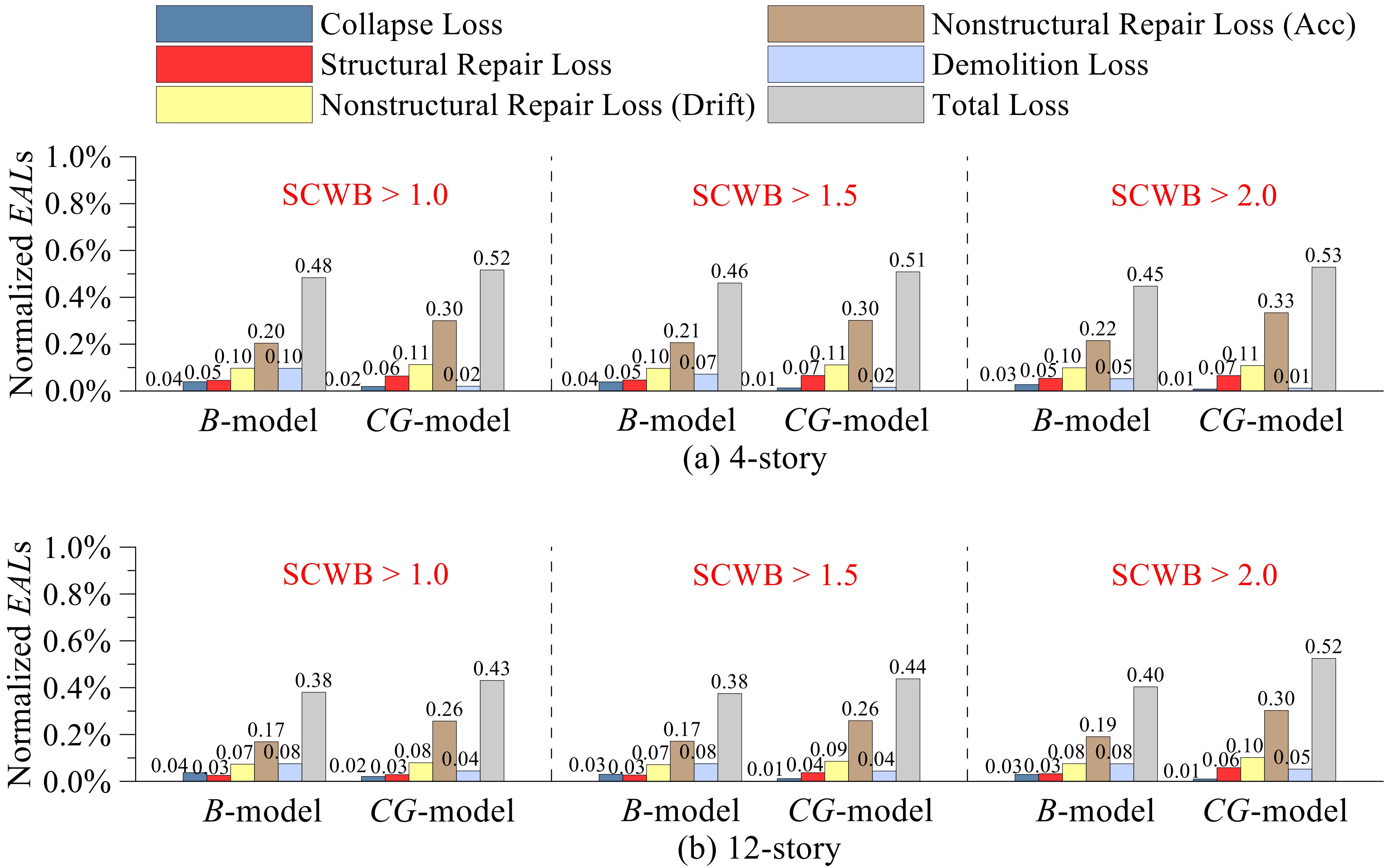
EAL weights all possible levels of the seismic hazard by taking into account their probability of occurrence.

$$E(L_T) = \int_0^\infty E(L_T|IM)\,\mathrm{d}\lambda(IM) = \int_0^\infty E(L_T|IM)\left|\frac{\mathrm{d}\lambda(IM)}{\mathrm{d}IM}\right|\mathrm{d}IM$$



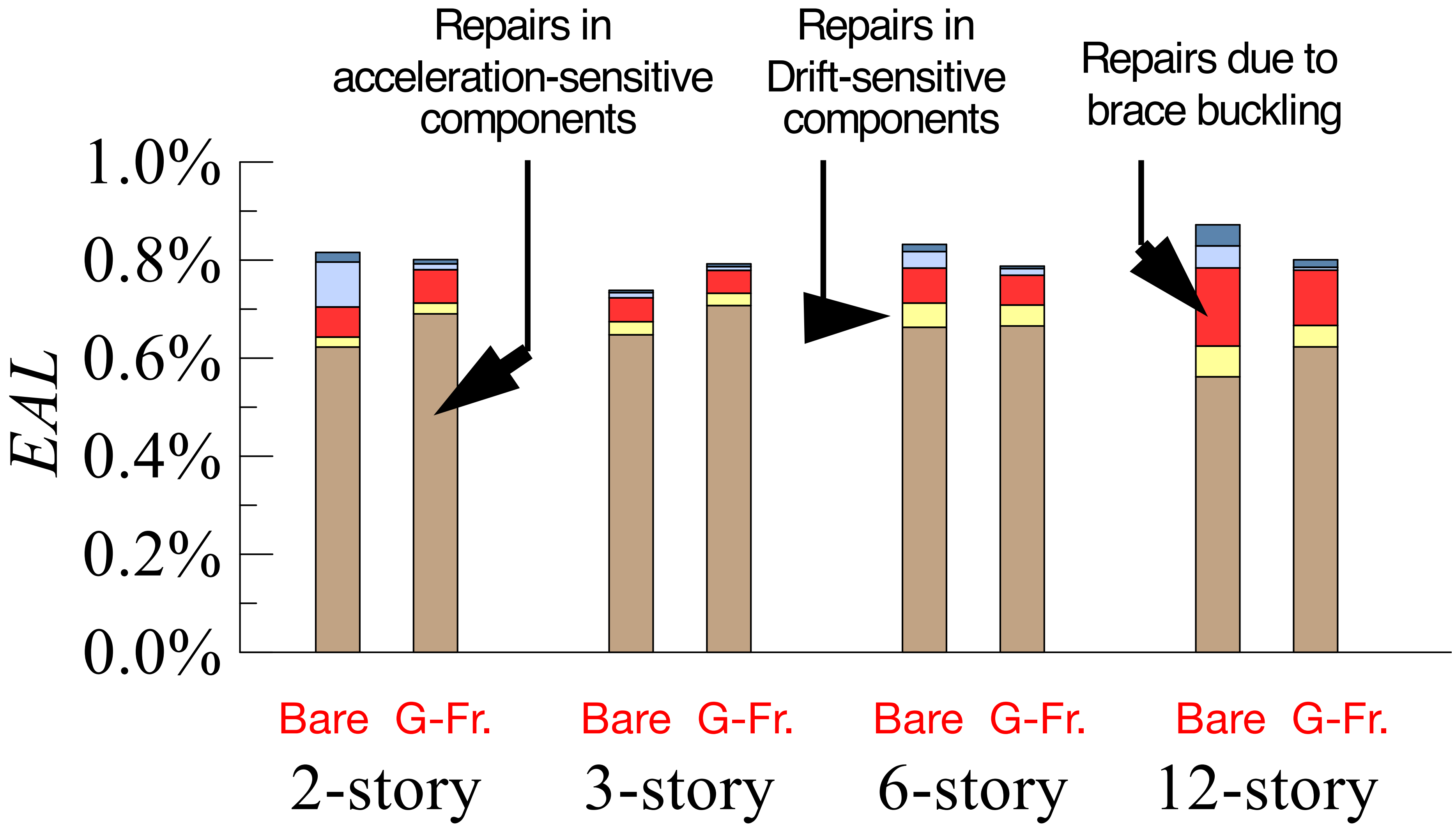


Expected Annual Losses (*EALs*)



*Hwang, S-H., Lignos, D.G. (2017). "Earthquake-induced loss assessment of steel frame buildings with special moment frames designed in highly seismic regions, *Earthquake Engineering and Structural Dynamics (EESD), Vol. 46(13),* 2141–2162. doi:10.1002/eqe.2898.

Expected Annual Losses – Steel CBFs



*Source: Hwang and Lignos (2017)**

*Hwang, S-H., Lignos, D.G. (2017). "Earthquake-induced loss assessment of steel frame buildings with special moment frames designed in highly seismic regions, *Earthquake Engineering and Structural Dynamics (EESD), Vol. 46(13),* 2141–2162. doi:10.1002/eqe.2898.

Concluding Remarks

- Gravity framing system reduces the collapse risk of up to 75%.
- At frequently occurring seismic events:
  - damage to non-structural content dominates losses regardless of the selected numerical model and lateral load resisting system
- Earthquake-induced loss estimates at discrete seismic intensities:
  - overestimated when building *EDP*s are based on "bare-frame" models (Losses due to demolition over predicted ~ by a factor of 2).
- Expected Annual Losses as a loss-metric:
  - Minor dependence on numerical model representation.
  - Main contributors: Repairs due to acceleration sensitive components followed by repairs due to steel brace buckling.

Thank you for your kind attention!

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