Implications of earthquake simulations on the nonlinear analysis and design of tall buildings

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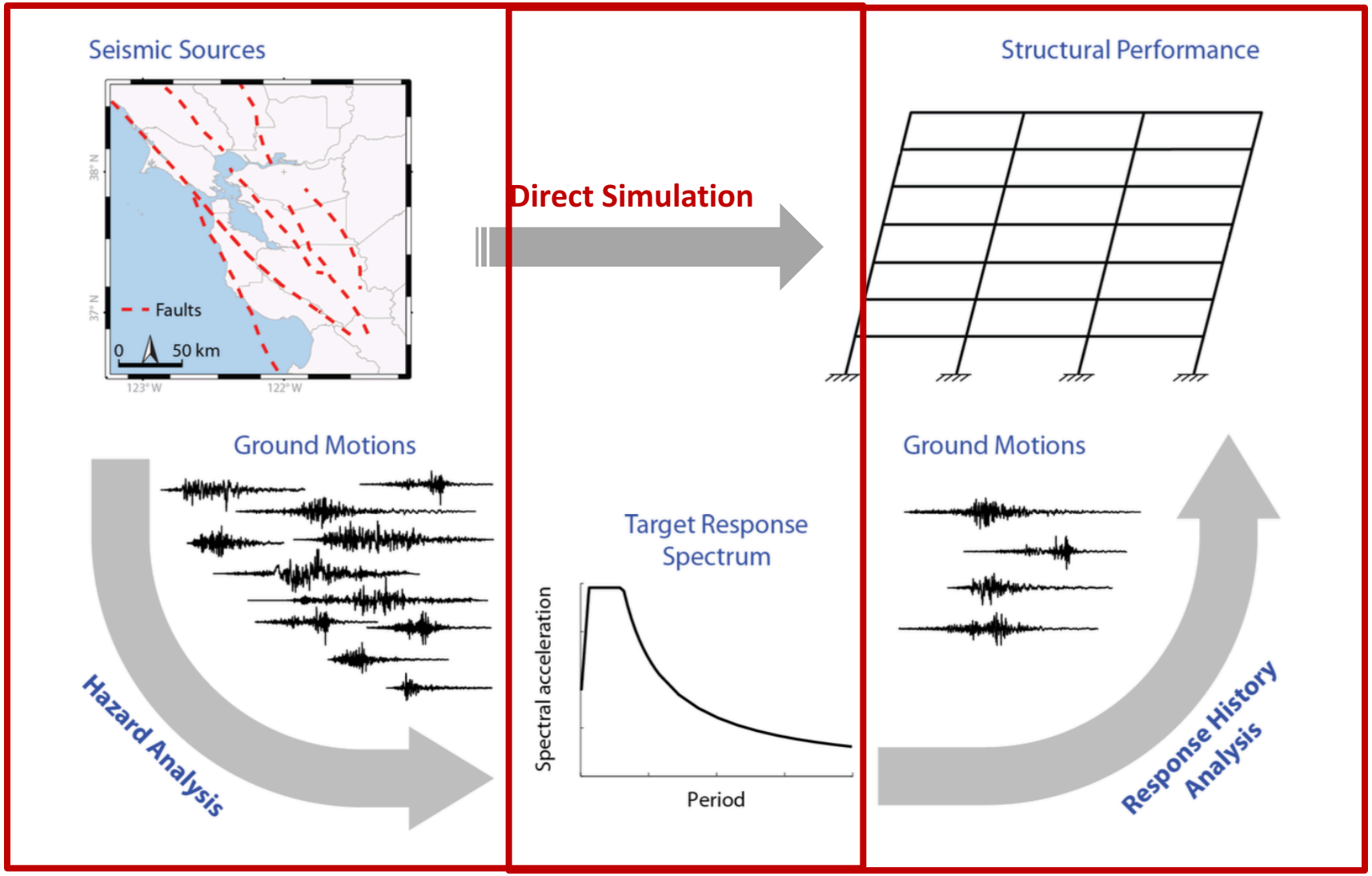
with contributions from

R. Chandramohan, J. Baker, R. Graves and SCEC GMSV Tag

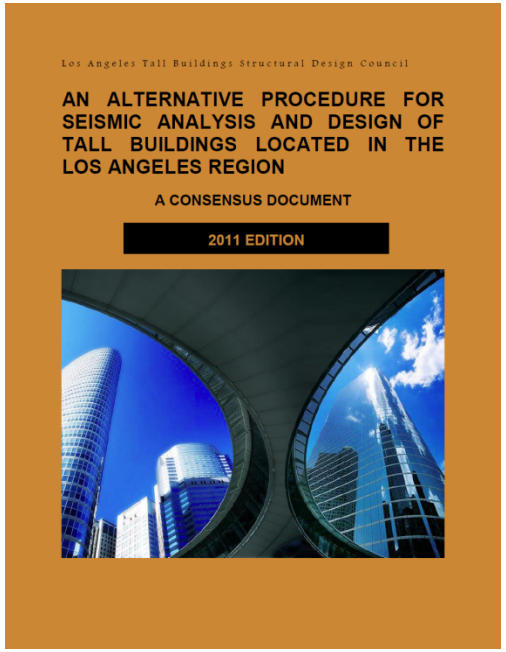
SCEC 2016 Annual Meeting

Use of EQ simulations in earthquake engineering



to determine Earthquake H dynamic analyses of structures

Seismic Design of Tall Buildings



Limit State Checks:

Service Level: essentially elastic under 43 yr return period motions (50% in 30 yr)

Story Drift Limit *– 0.5% (mean)*

MCE_r Level: sufficient margin against collapse as demonstrated by ***nonlinear dynamic (response history) analysis*** *under Maximum Considered Earthquake motions (1000 yr to 2500 yr; 2% to 5% in 50 yrs)*

Story Drift Limits

Mean Peak: 3.0%

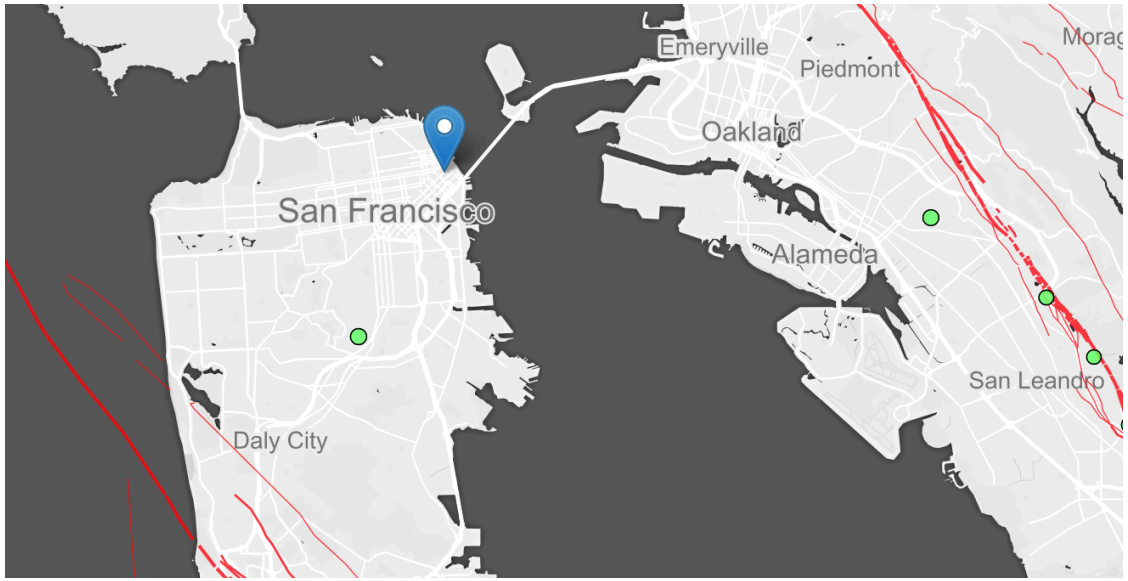
Maximum Peak: 4.5%

Mean Residual: 1%

Structural Component Checks

force-controlled & deformation-controlled

Seismic Design of Tall Buildings



EQ Hazards and Ground Motions

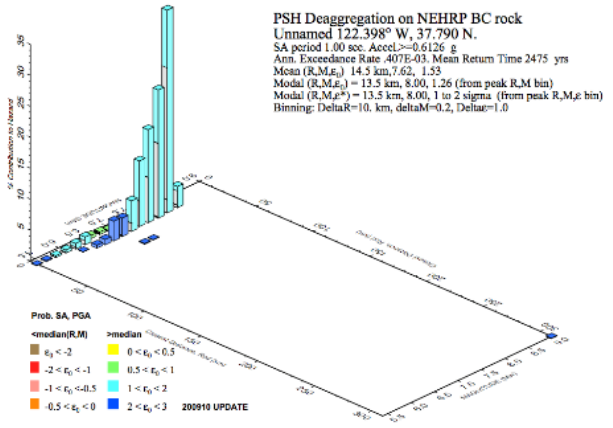
MCE_r Intensity - lesser of:

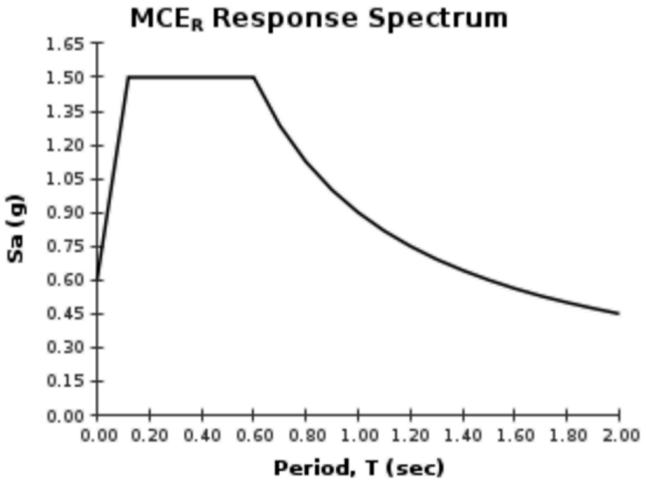
- 2% in 50 year hazard spectrum
- deterministic cap

Downtown SF deterministic cap:

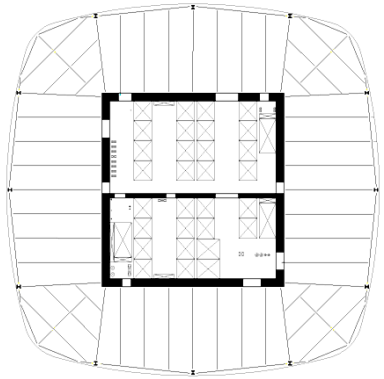
M7.9 @ 13.8km on San Andreas Fault

Mean + 1σ (84th percentile)





Seismic Design of Tall Buildings



Sales Force (Transbay) Tower

- 1,070 feet tall
- Office occupancy
- Concrete Shear Wall w/coupling beams
- Permitted under 2010 San Francisco Building Code, including AB-083, PEER TBI
- Design team:

  Architects – Pelli Clarke Pelli

  Structural – Magnusson, Klemencic & Assoc.

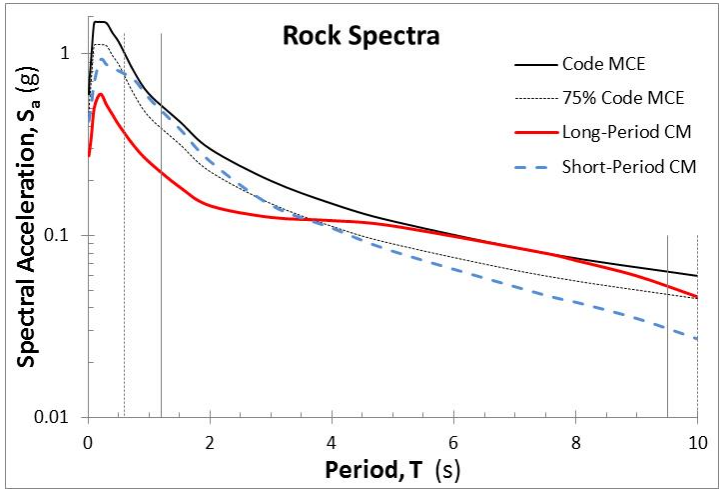
  Geotech – ARUP

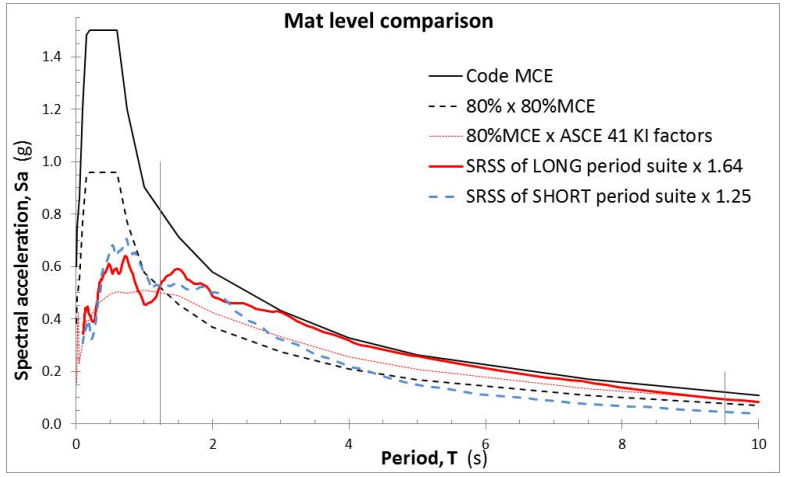
  Mechanical/Electrical - WSP

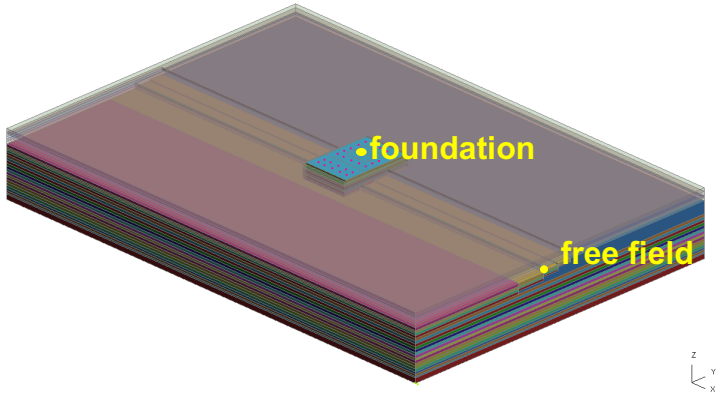
Seismic Design of Tall Buildings

Ground Motion MCE_r (M8, 13.8 km Hazard Spectra

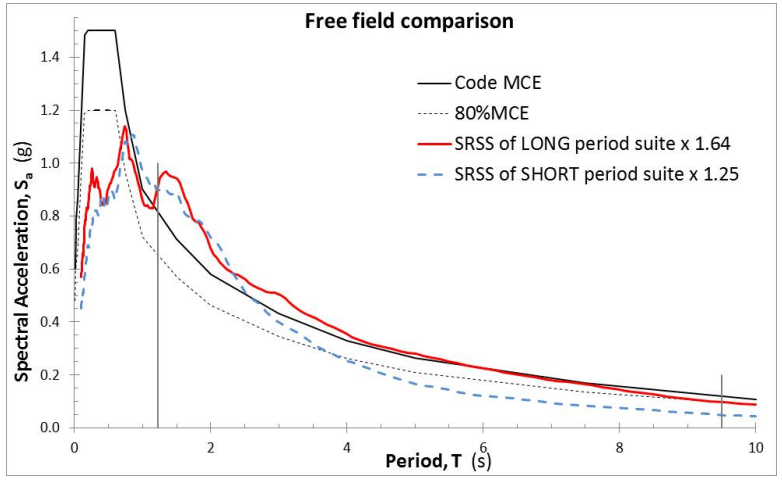
1. PSHA with GMPE's to determine rock spectra (UHS and CMS)
2. Select and scale 11 ground motion pairs to rock spectra (from PEER NGA database)
3. 3D FEM site model (~60 m deep) to propagate ground motions
4. Calculate average spectra of resulting motions at tower foundation and free field
5. Scale resulting ground motions to meet lower limits of ASCE 7 criteria, based on free field hazard







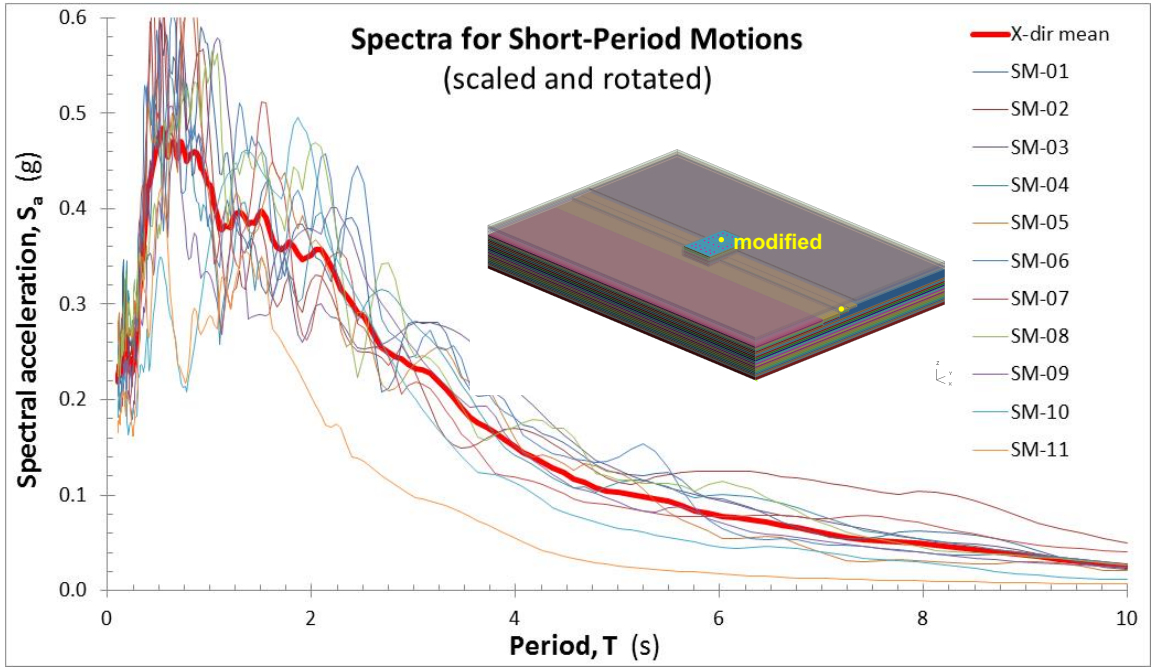
LS-DYNA Site Model



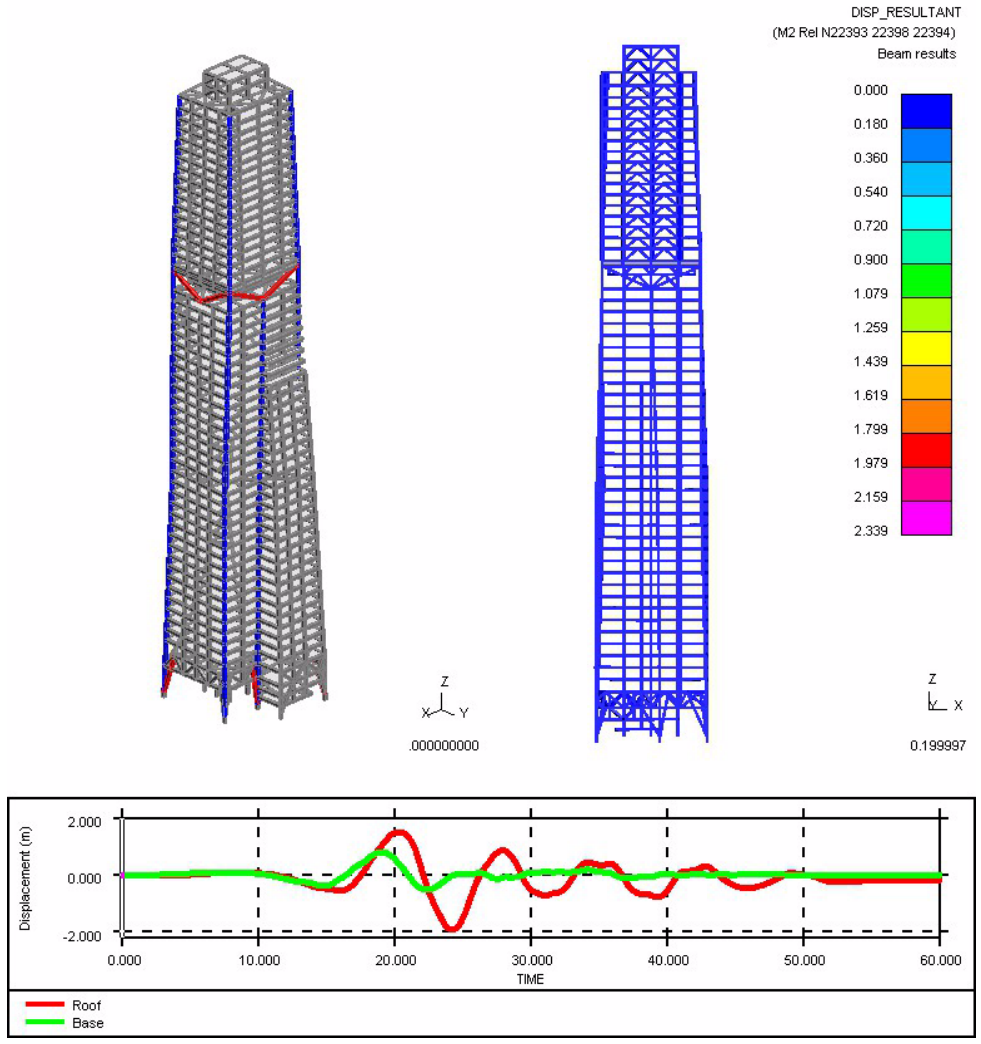
Hooper et al. (2015) EERI Tall Buildings Seminar

Seismic Design of Tall Buildings

Apply Ground Motions to Building Model



- Ground motions from 3D FEM at foundation level
- 11 pairs for each CMS target

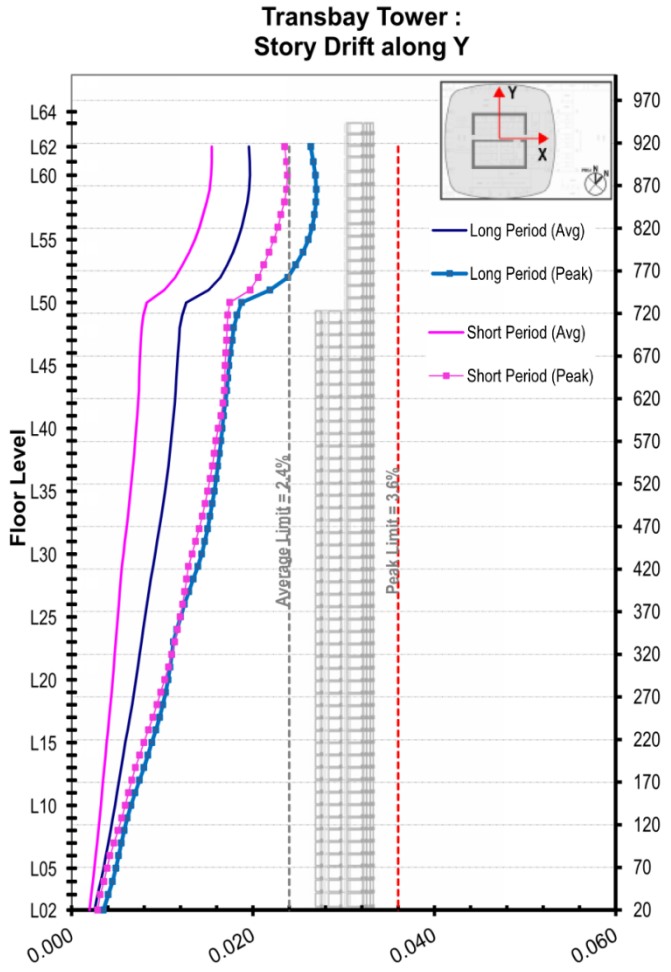


Nonlinear Response History Analysis
(animation is 181 Fremont Tower by ARUP)

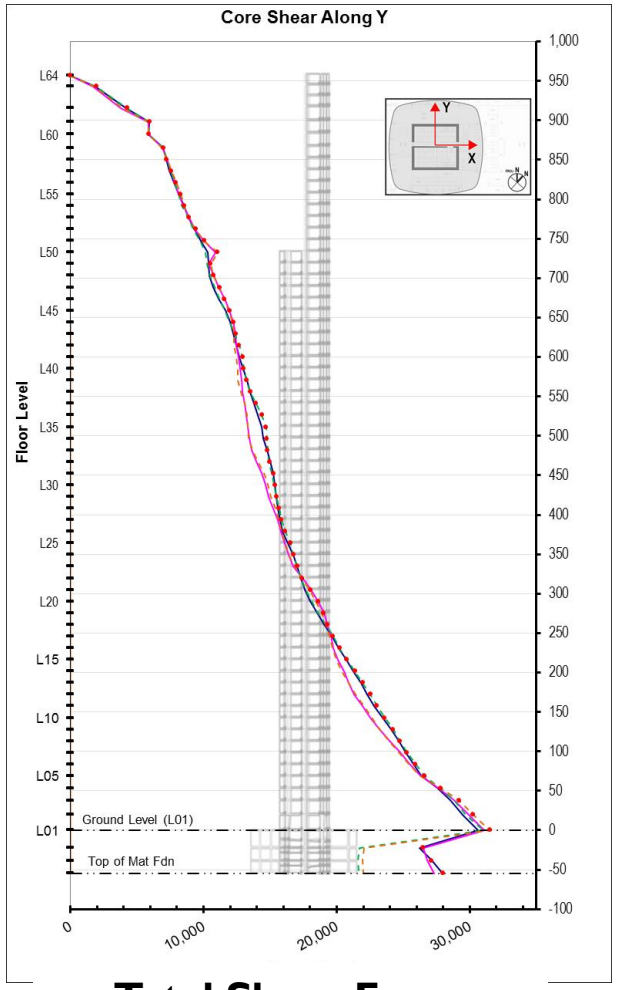
Hooper et al. (2015) EERI Tall Buildings Seminar

Seismic Design of Tall Buildings

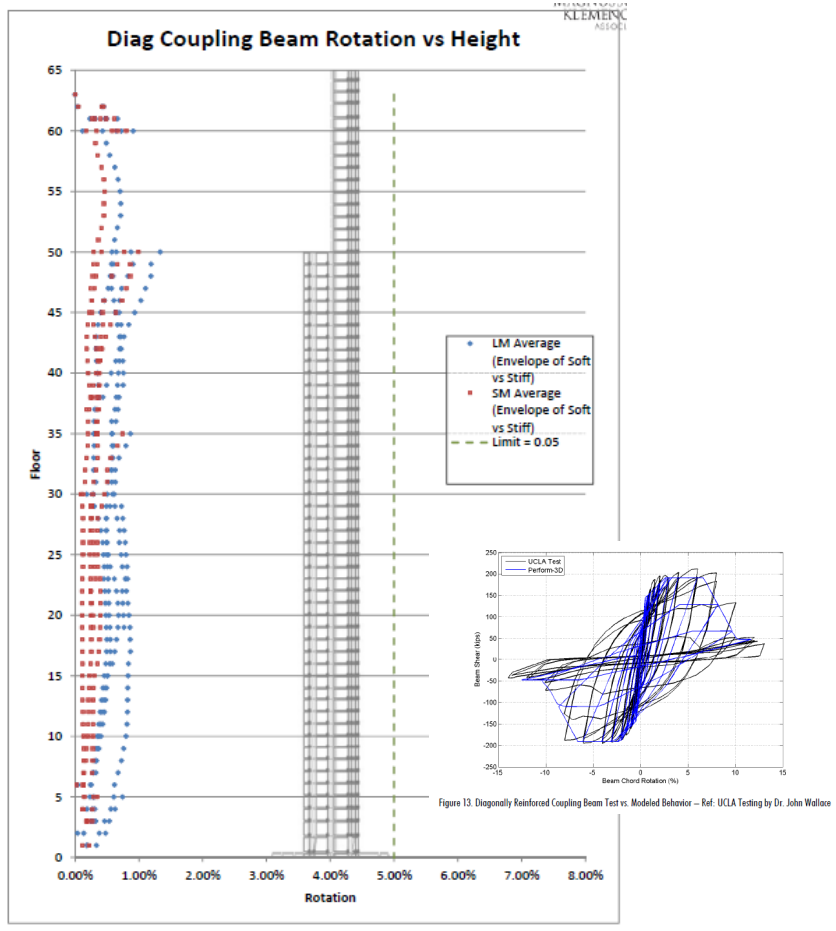
Evaluate Resulting EQ Demands on Building



Story Drift Ratios



Total Shear Force



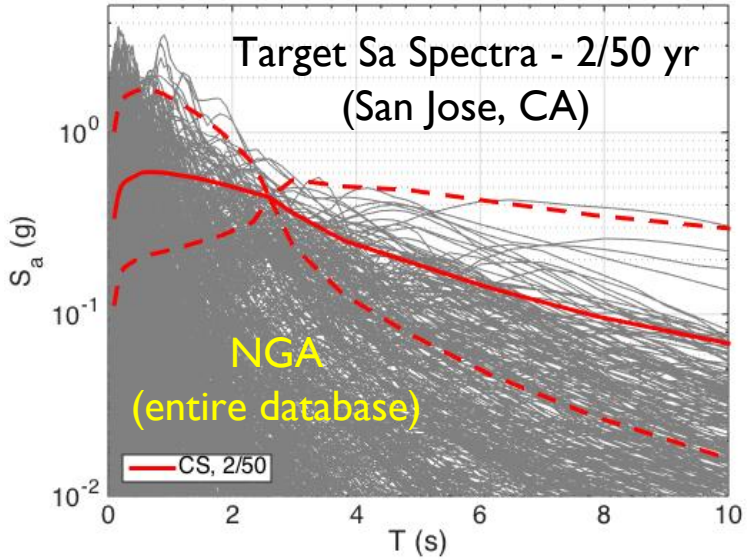
Inelastic Coupling Beam Rotations

Hooper et al. (2015) EERI Tall Buildings Seminar

Characterizing Input Ground Motions

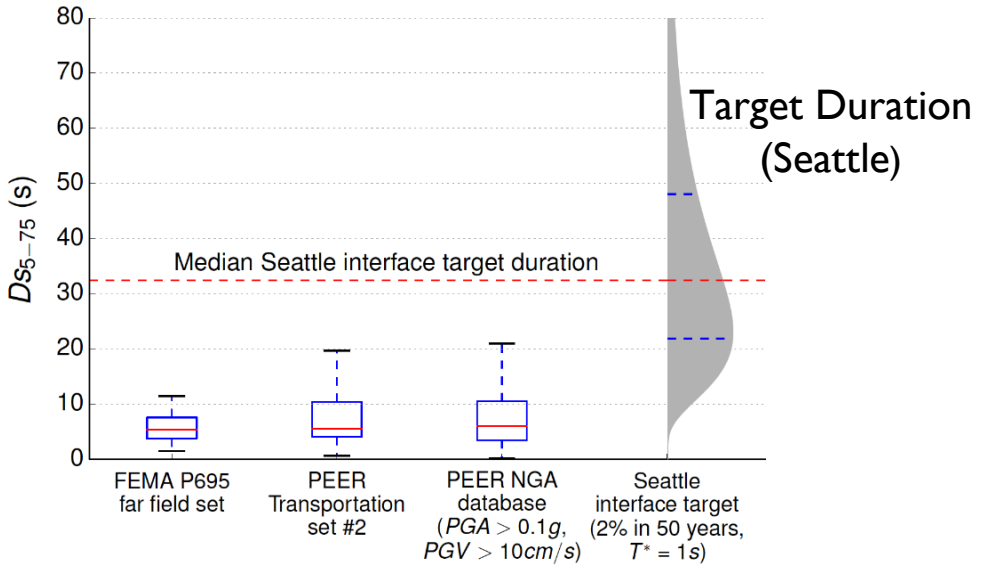
Current Practice (ASCE 7)

- PSHA with GMPE's to determine target Sa spectra (intensity & shape)
- Select motions with representative "causal features"
  e.g., fault type, M, R, pulses …
- Scale (match?) ground motions to target spectra



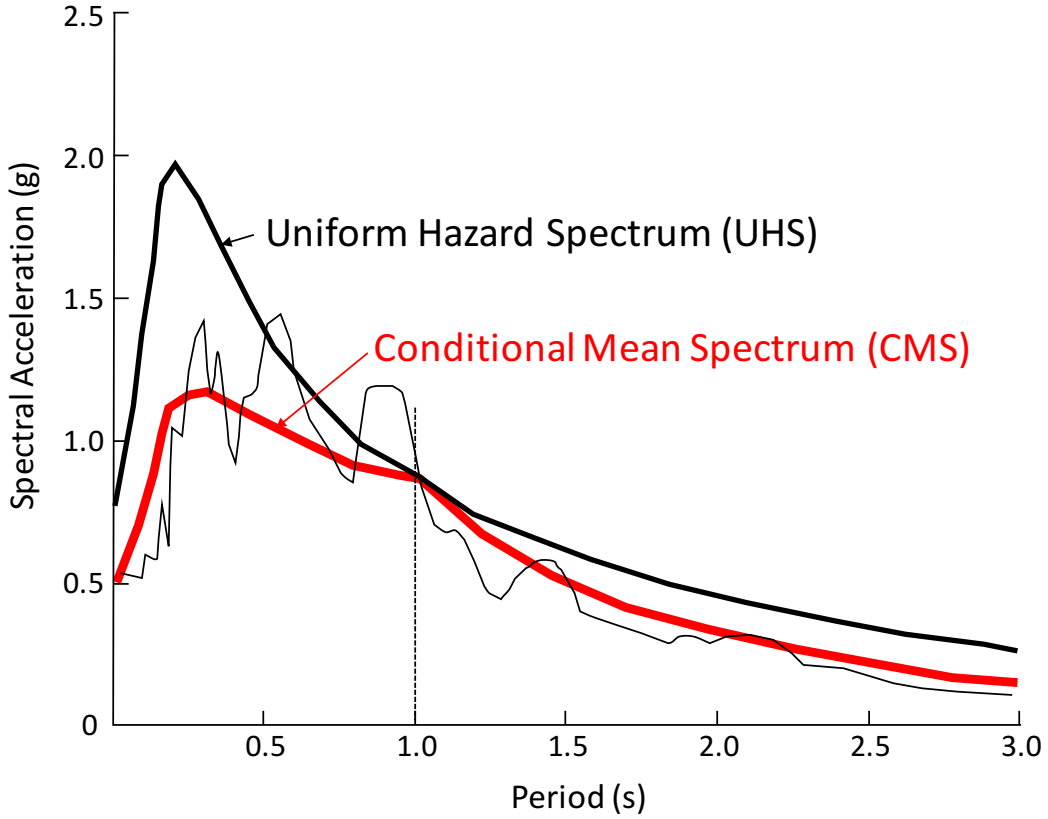
Shortcomings & Limitations

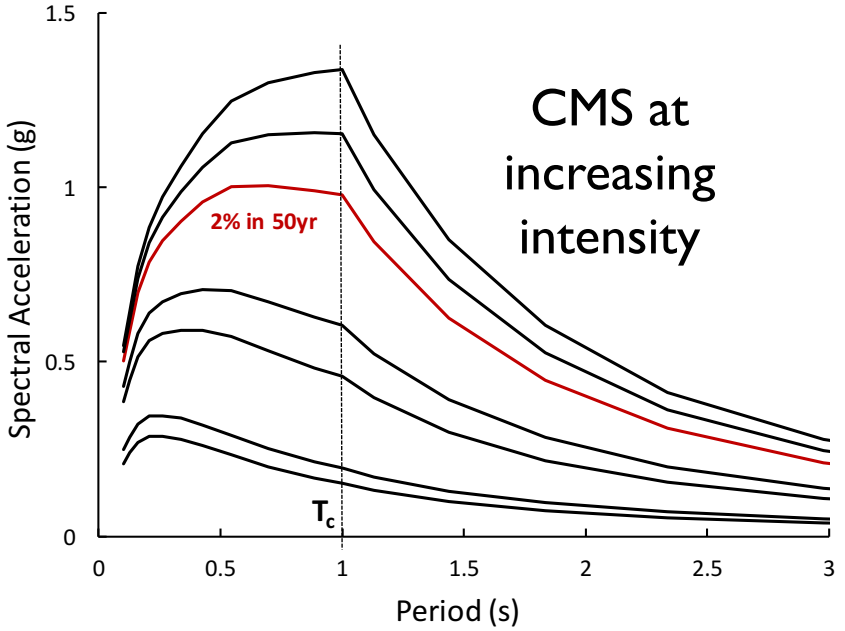
- Reliance on empirical GMPE's
- Shortage of representative ground motions
  - large M, short R
  - high intensity
  - long duration
  - directivity pulses

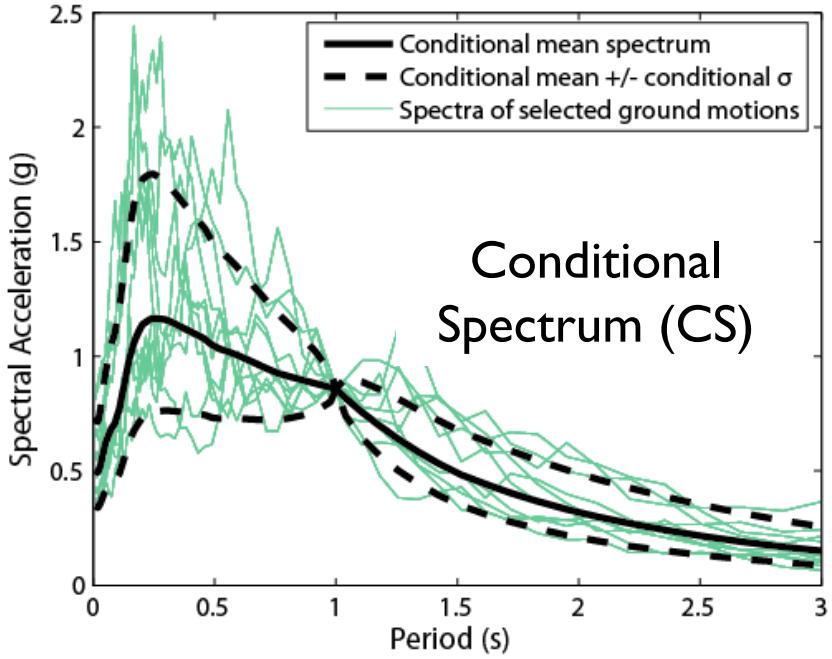


Bijelic, Chandramohan et al.

More Explicit Ground Motion Targets



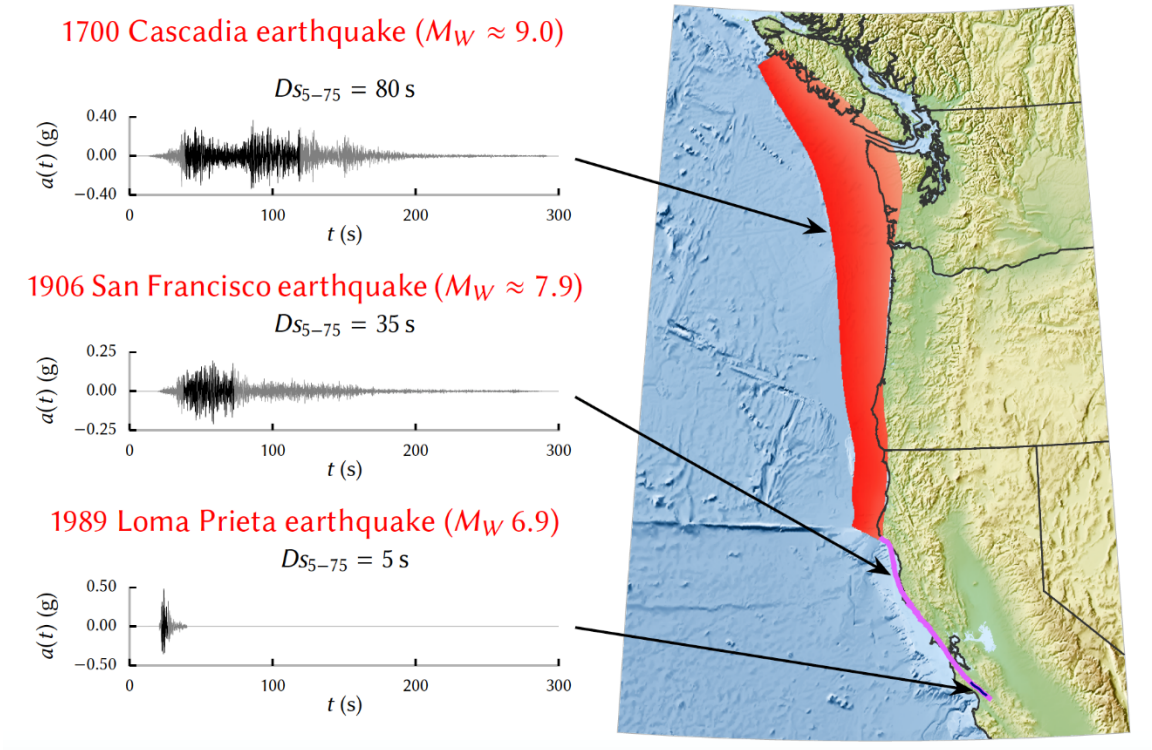


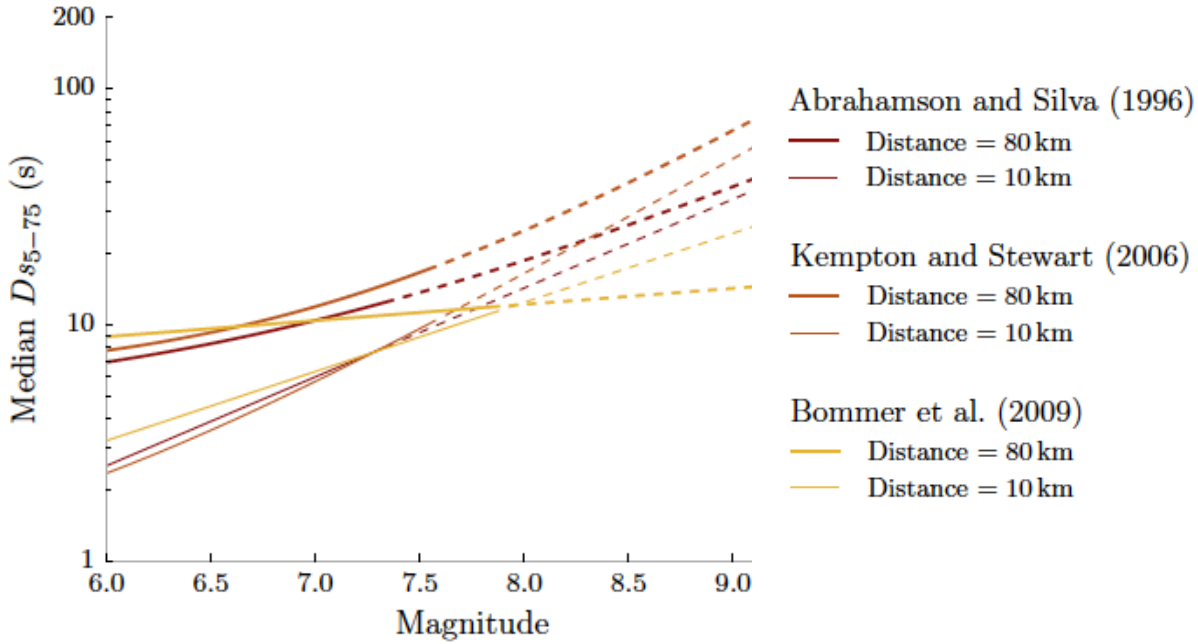


Spectral Shape & Variability

Baker et al., NIST GCR 11-917-15

More Explicit Ground Motion Targets



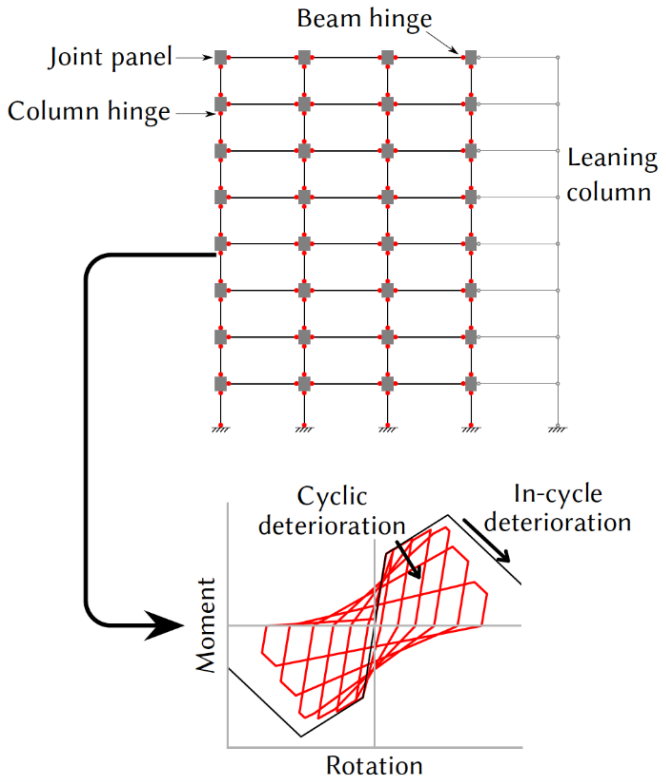


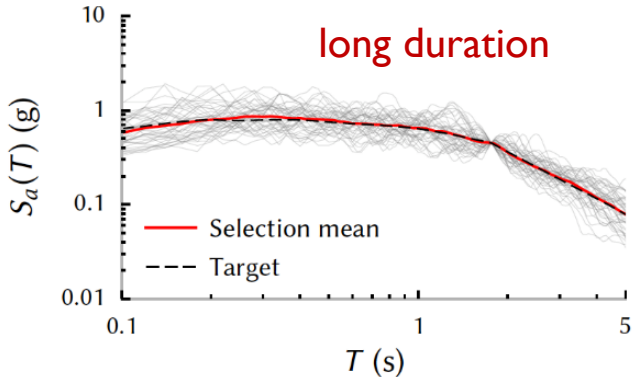
Ground Motion Duration
(Significant Duration, $D_{s5\text{-}75}$)

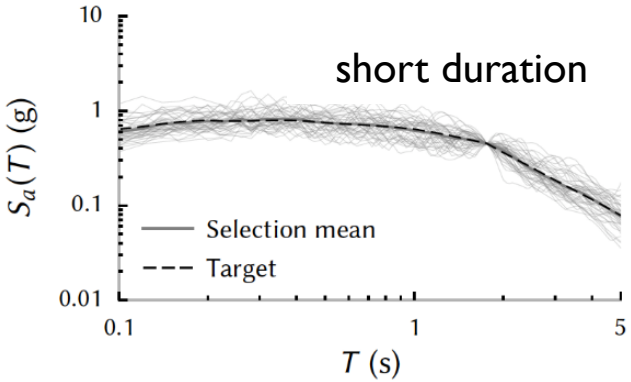
Empirical Duration (D_s) Prediction Equations

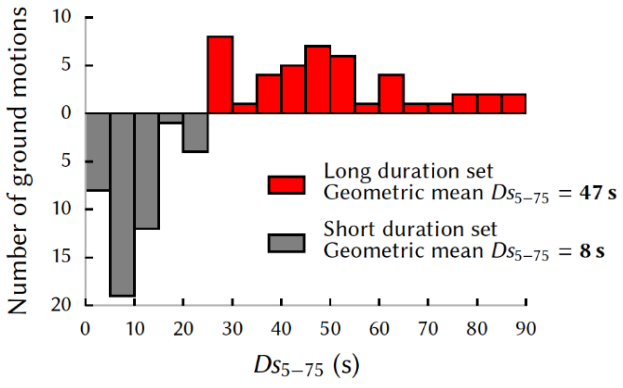
Chandramohan, Baker, Deierlein

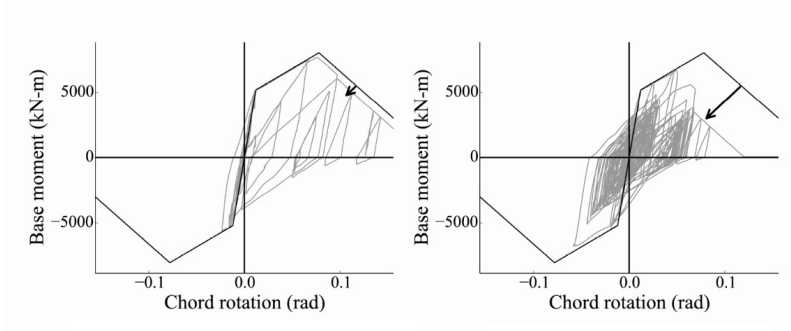
Influence of Duration on Structural Collapse

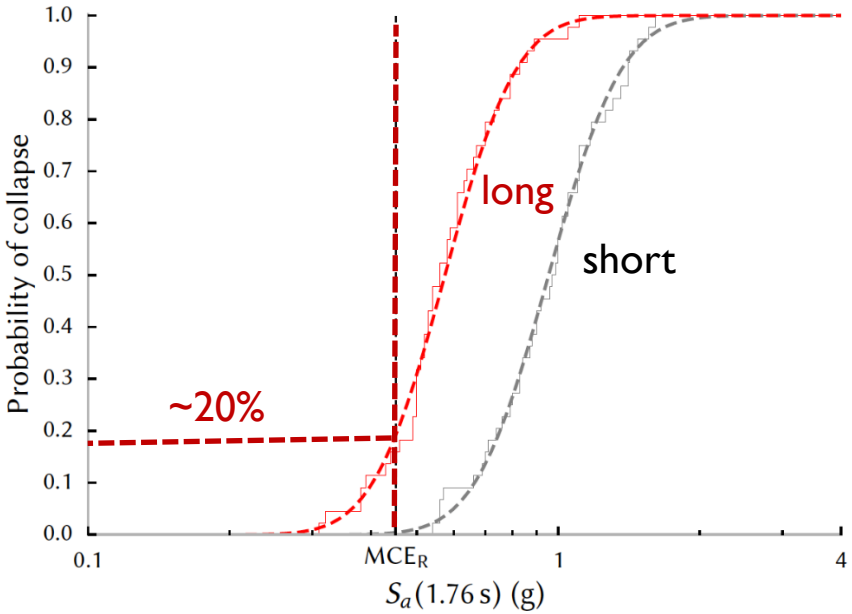












Collapse Fragility Curve

Comparison of collapse capacity, determined using two sets of spectrally equivalent records with different durations

Chandramohan, Baker, Deierlein

Combined CS & Ds Hazard Targets

Generalized Conditional Intensity Measure (GCIM)

- Establish CS Target (Sa)
- Establish Duration Target (Ds)
- Choose & Scale Ground Motions to Match

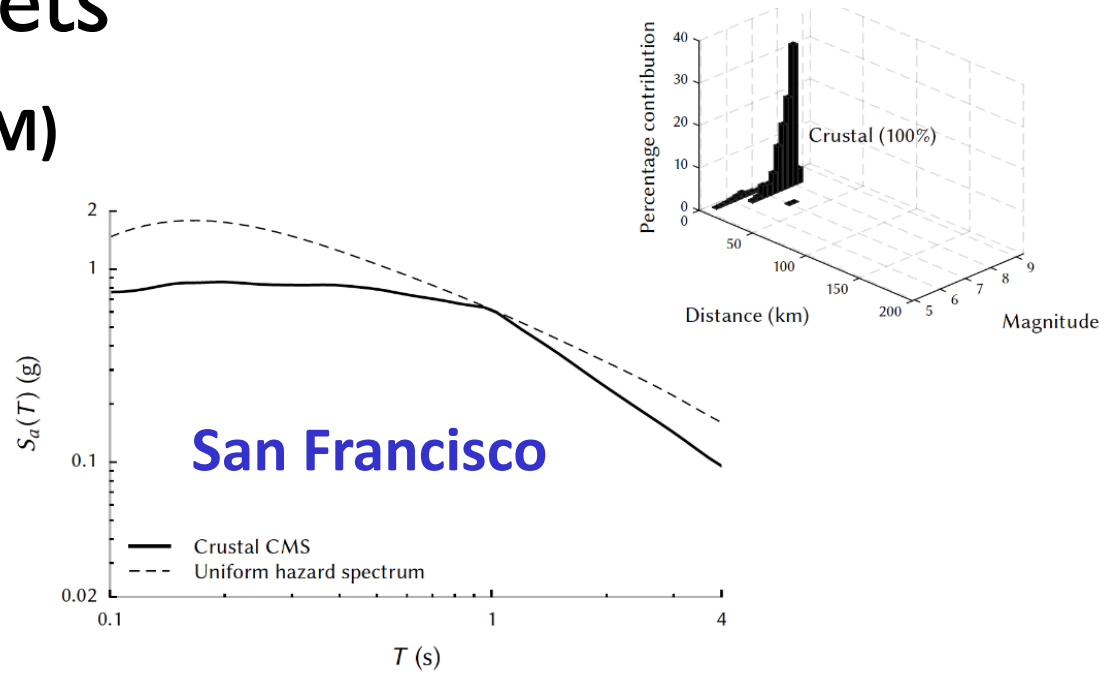
For Sites with multiple source zones

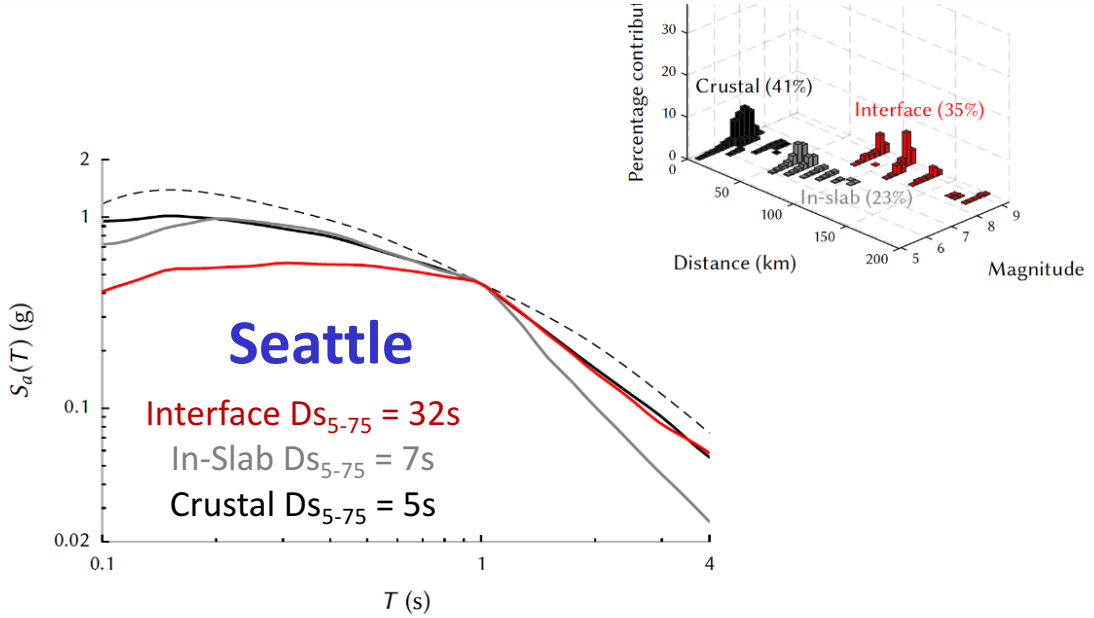
Option 1:

- Establish Multiple CS/Ds Targets
- Select and Scale Ground Motions for Each
- Run Analyses for Each Set
- Combine Results of Multiple Sets

Option 2:

- Develop Average CS/Ds Target
- Proceed as with standard approach

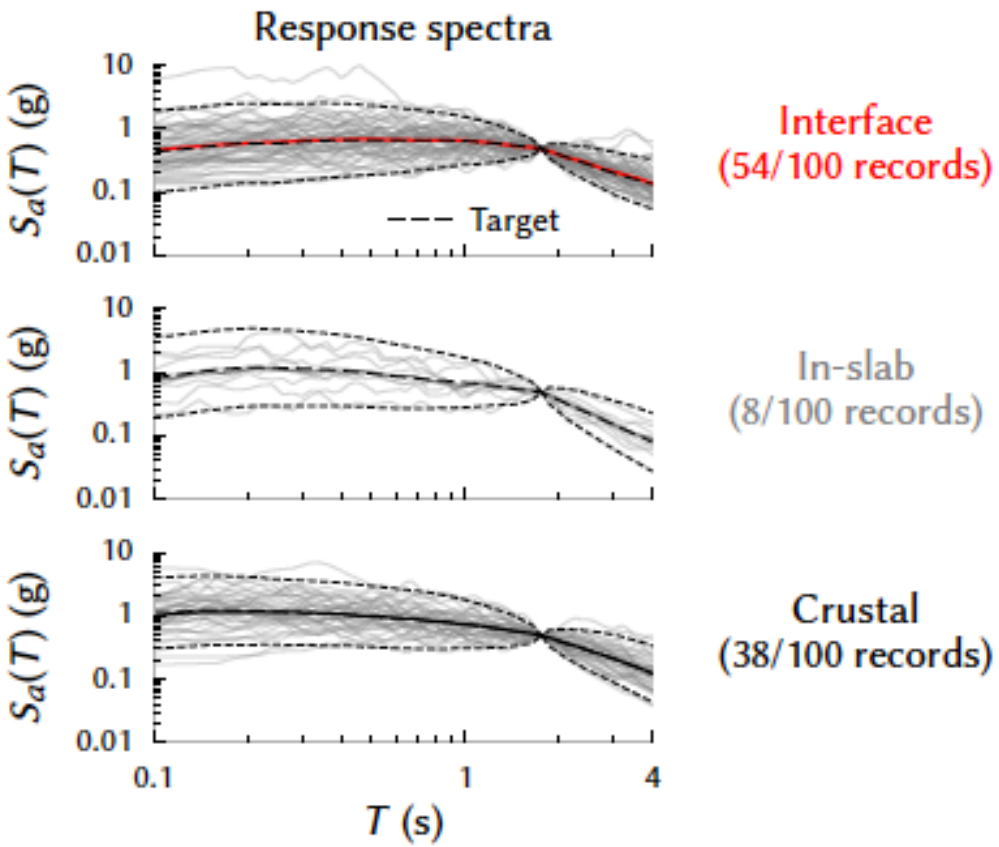




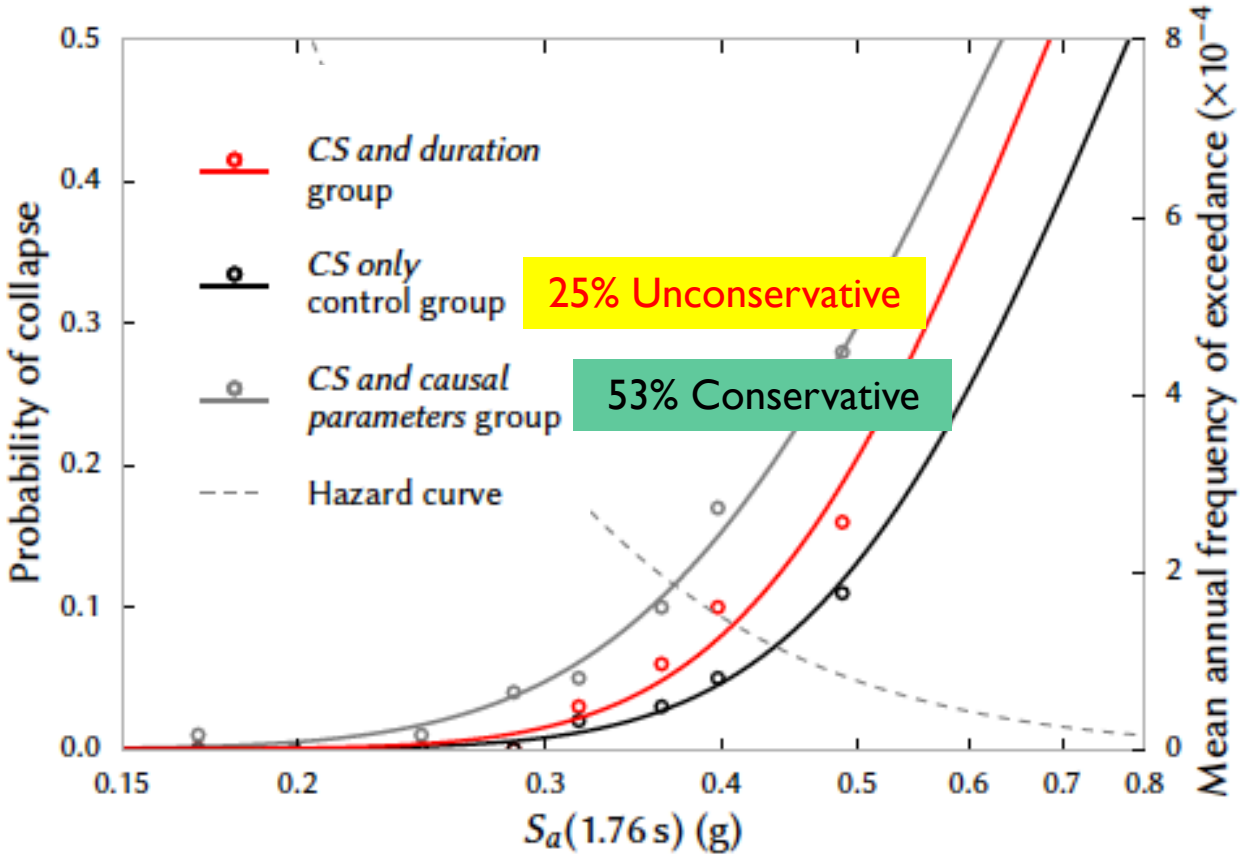
GCIM Method (Bradley, 2010)

EQ Duration Study (Chandramohan, Baker, Deierlein, 2016)

Comparison of Collapse Results – Alternative Targets



Seattle Hazard

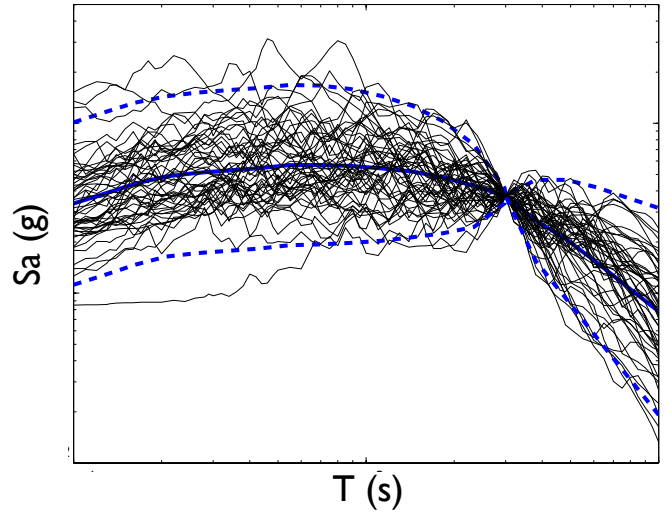


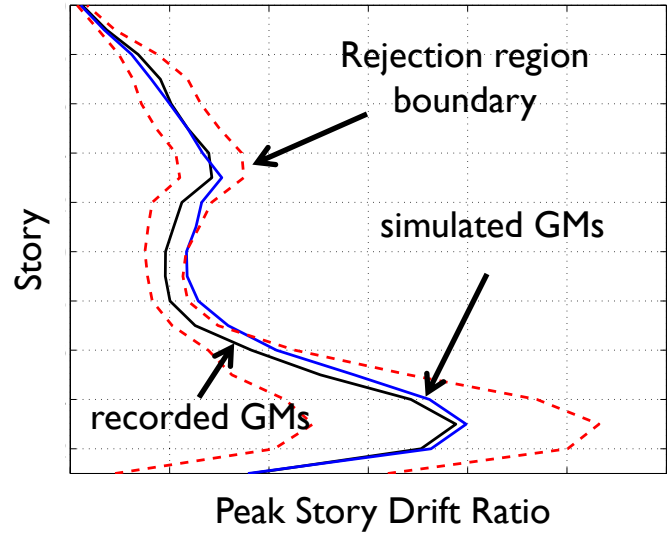
Seattle Collapse Fragilities

EQ Duration Study (Chandramohan, Baker, Deierlein, 2016)

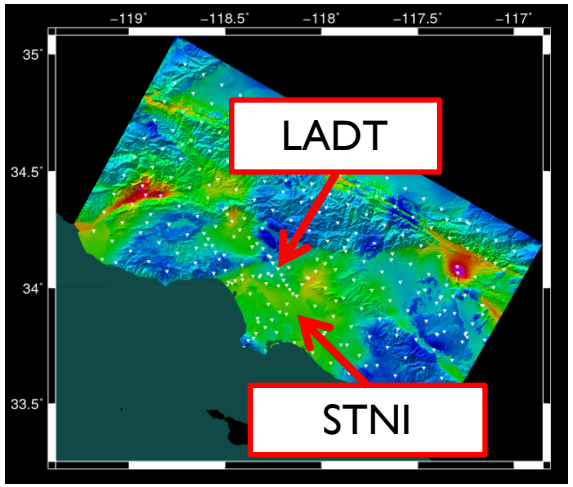
Engineering Applications/Validations with Simulated Motions

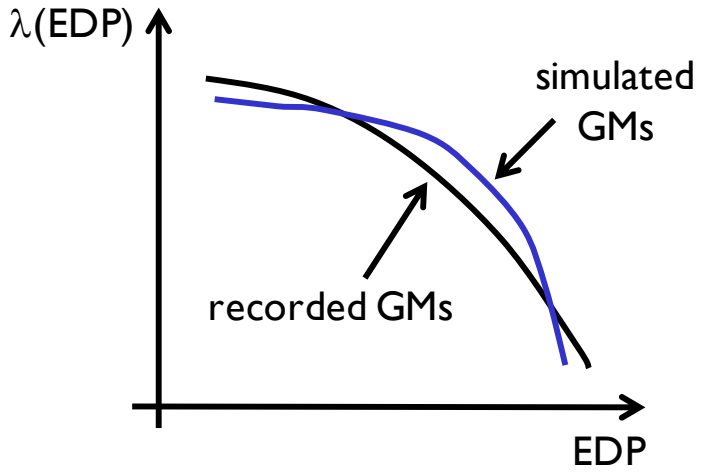
Similar Intensity Measure (IM)



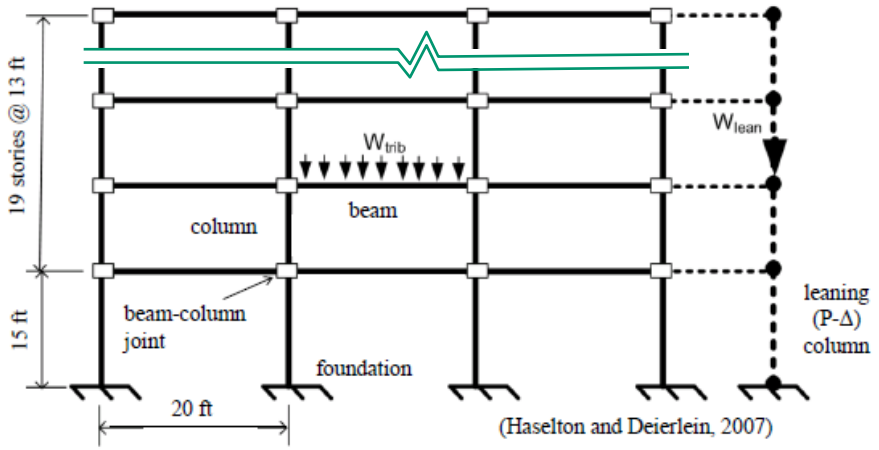


Conventional vs. CyberShake





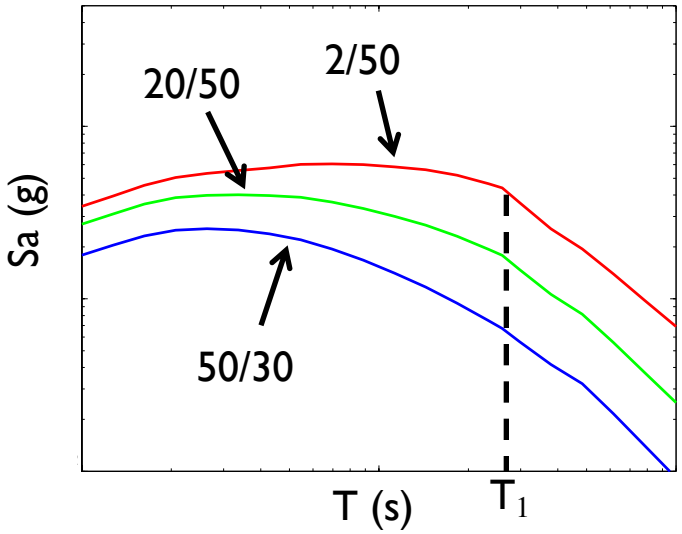
Engineering Application: Similar IM

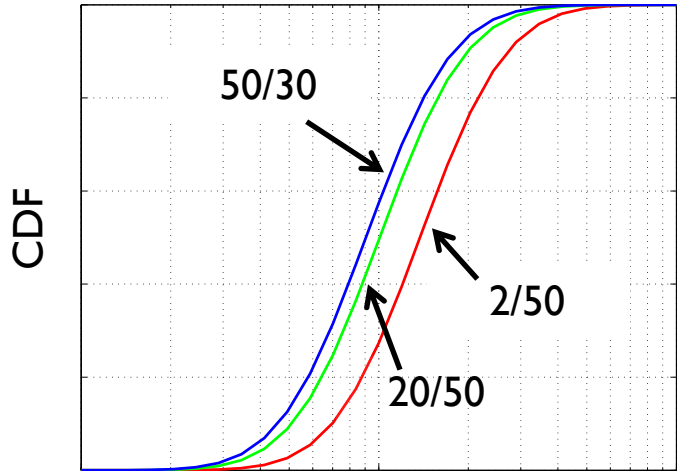


20-story RC moment frame, T_1 = 2.60s

BBP Validation Runs for Past Earthquakes		
Scenario	**Mw**	**Ground motion model**
Loma Prieta (BBP, 13.5)	6.9	
Northridge (BBP, 13.5)	6.7	*GP* (Graves-Pitarka, 2015)
Whittier Narrows (BBP, 13.5)	6.0	*SDSU* (Olsen-Takedatsu, 2015)
North Palm Springs (BBP, 13.6)	6.1	*EXSIM* (Atkinson- Assatourians, 2015)
Landers (BBP run 13.5)	7.3	

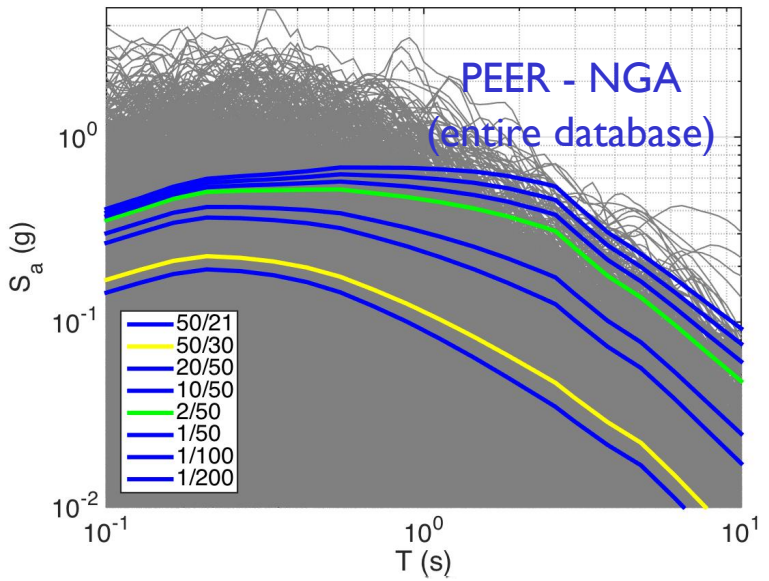
Source: Google Earth

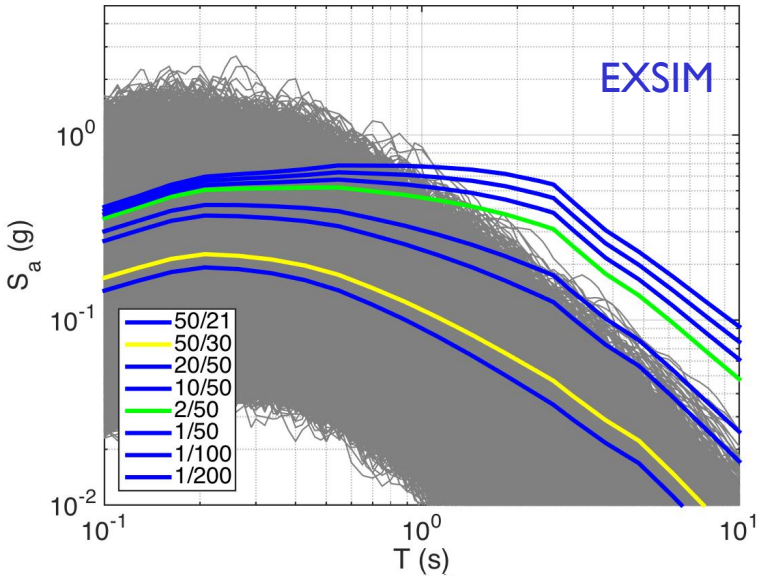


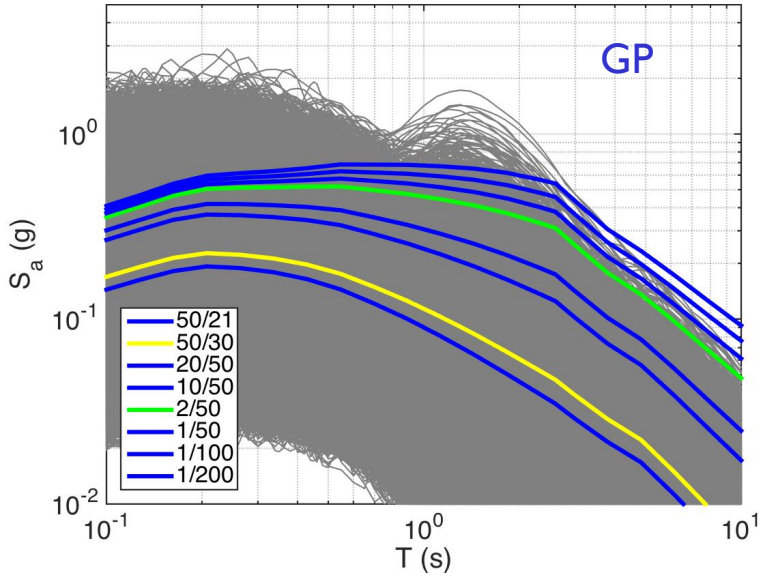


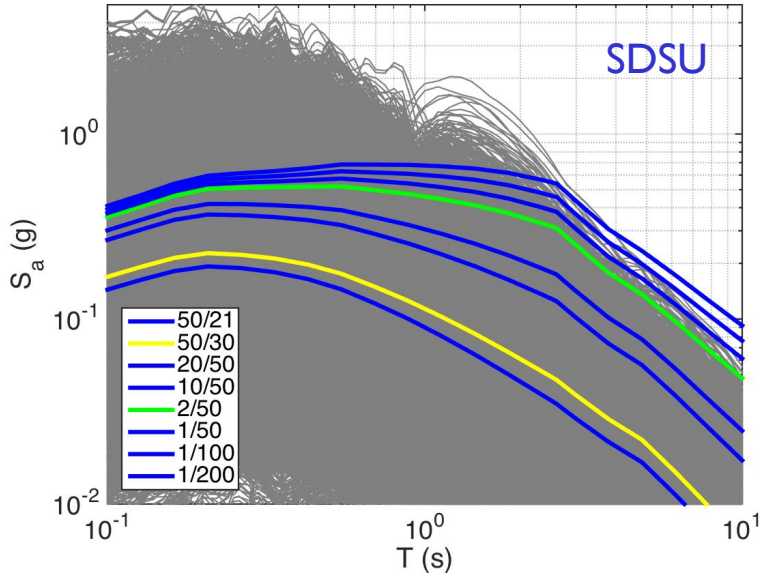
Conditional Spectra and Duration Targets for San Jose

Engineering Application: Similar IM

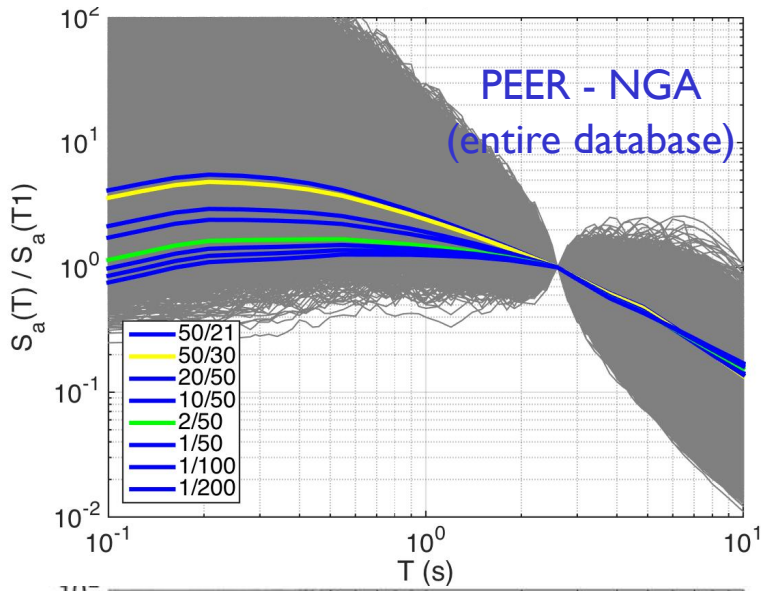


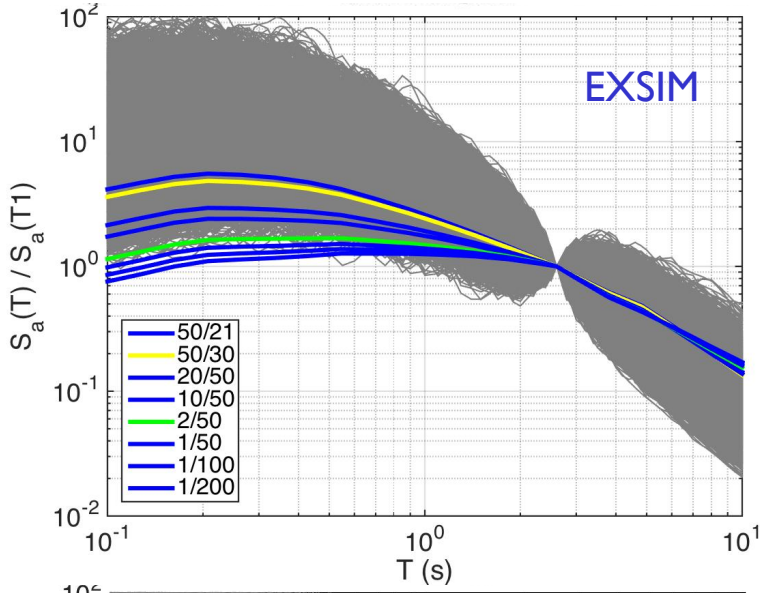


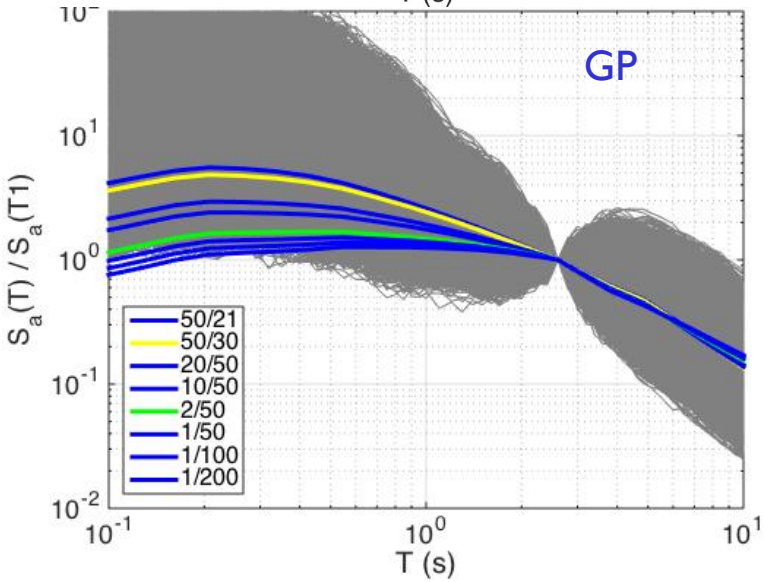


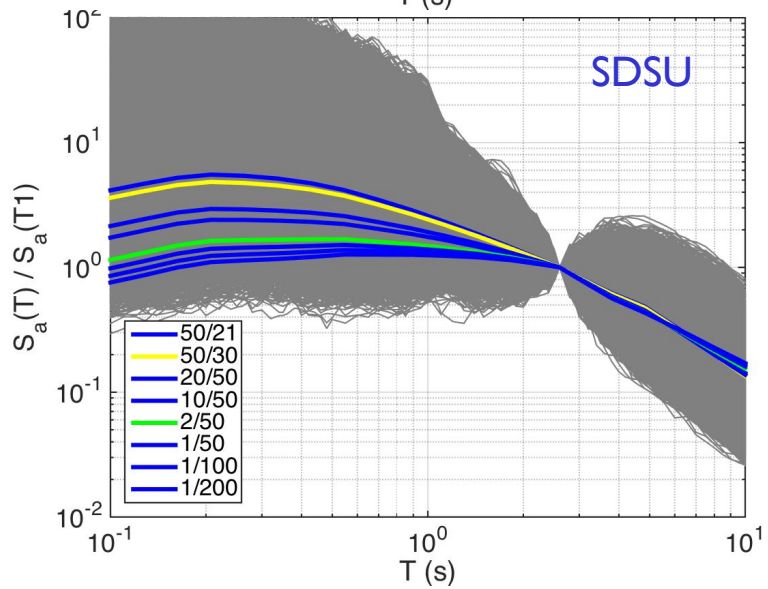


Engineering Application: Similar IM





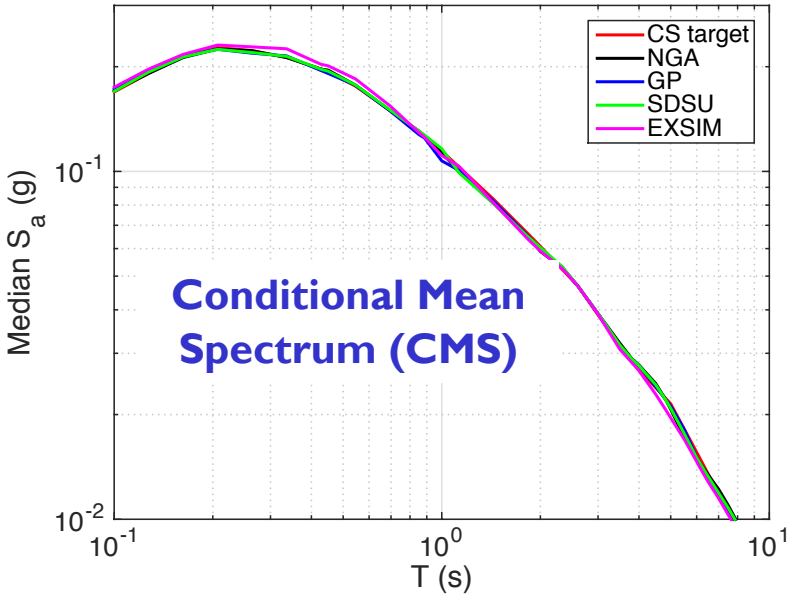


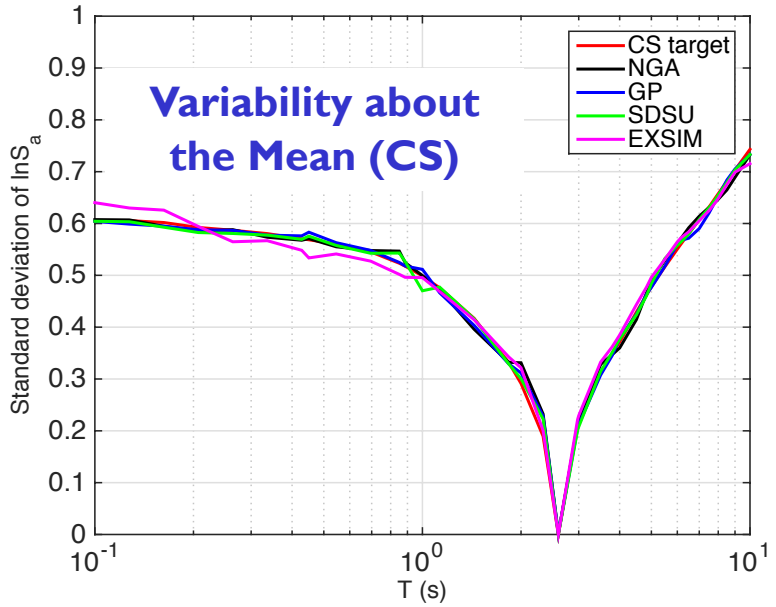


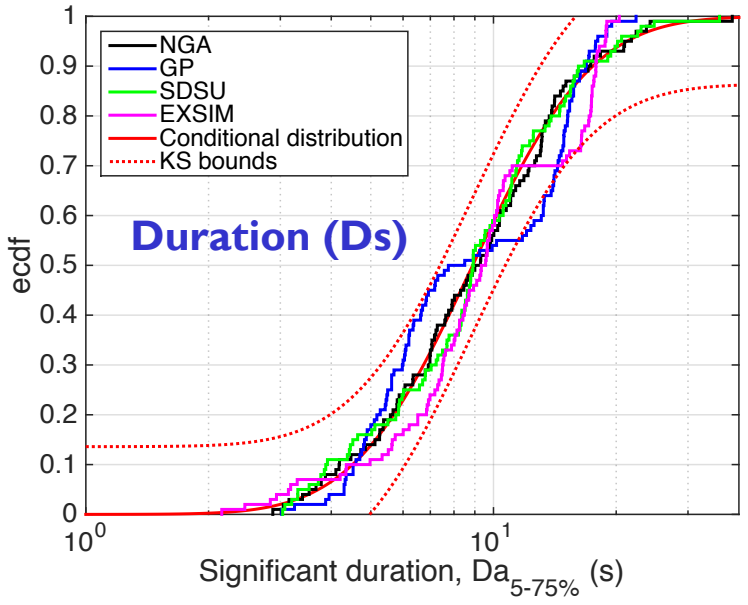
Engineering Application: Similar IM

- Conditional spectra and significant duration targets developed for a scenario R = 40.5 km, M = 6.95 km

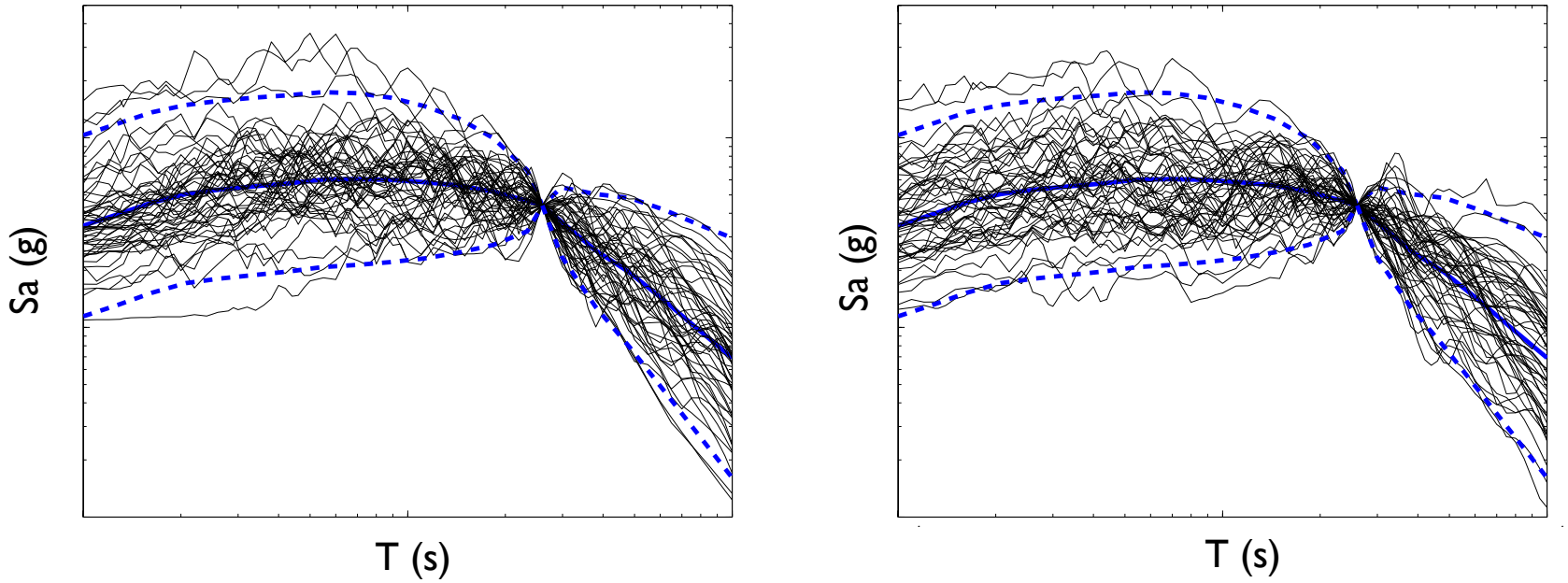
- Selected sets (100 motions in each set) match the conditional spectra and significant duration targets very well







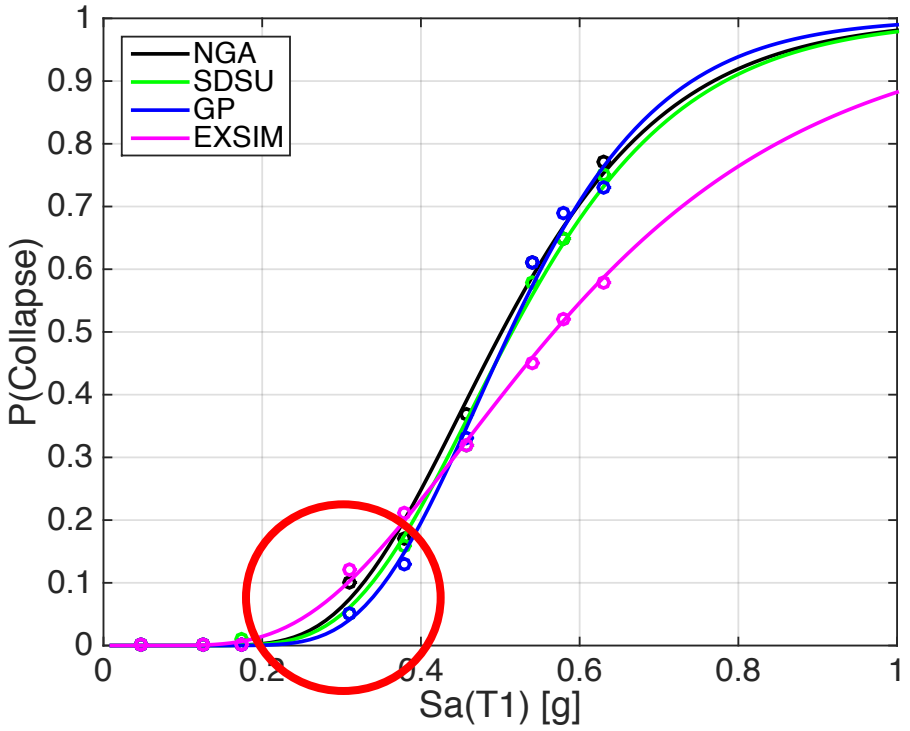
Engineering Application: Similar IM



Which set consists of simulated versus recorded motions?

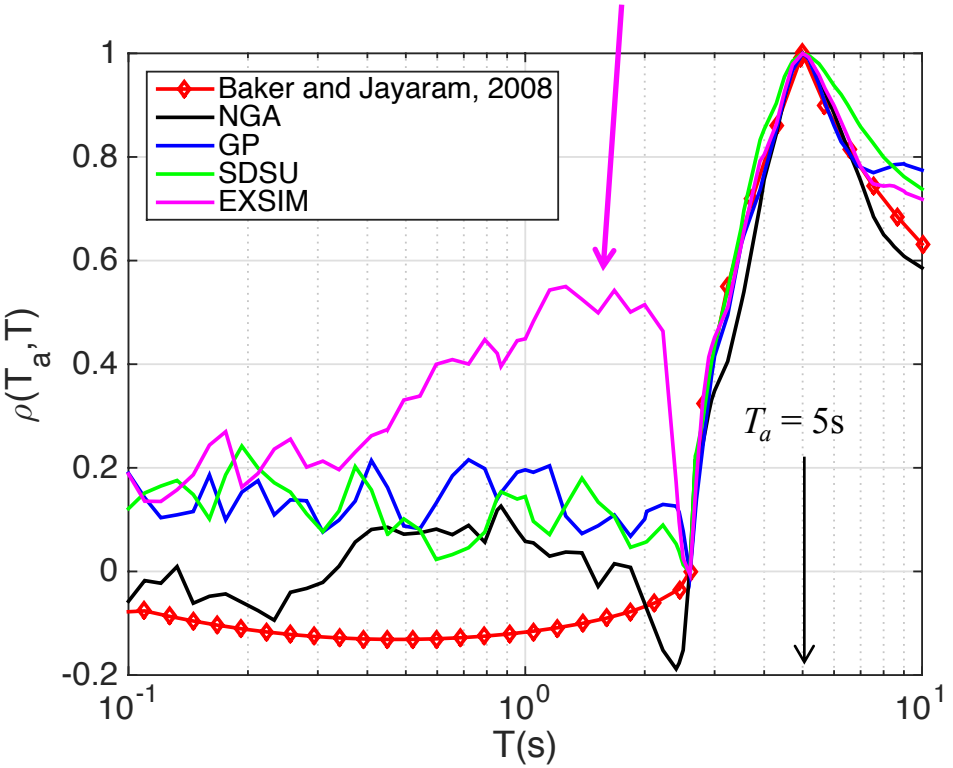
Engineering Application: Similar IM

EXSIM set was more damaging (higher collapse risk) than others



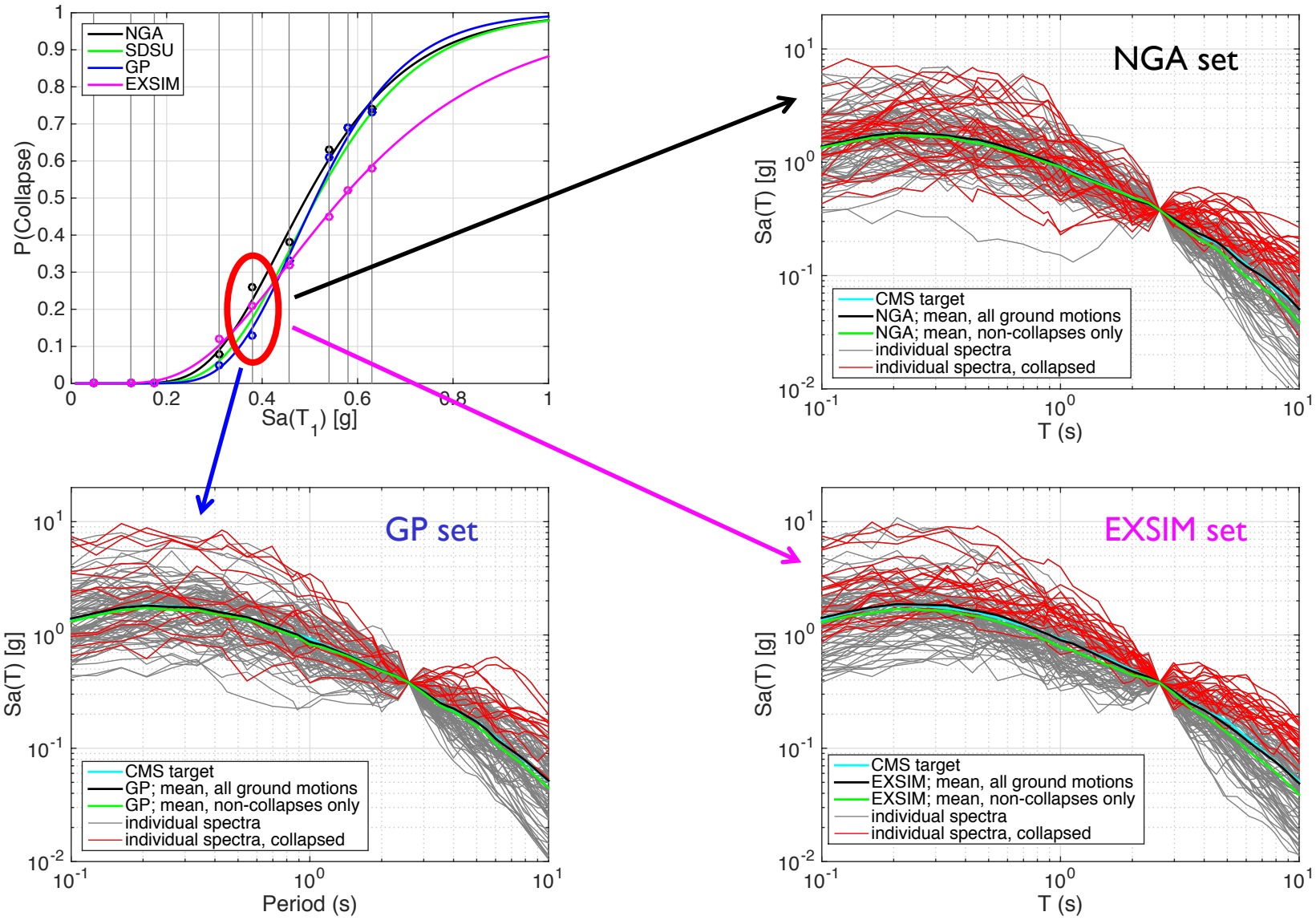
Collapse Fragility

Sa correlation across periods - EXSIM much higher than NGA set



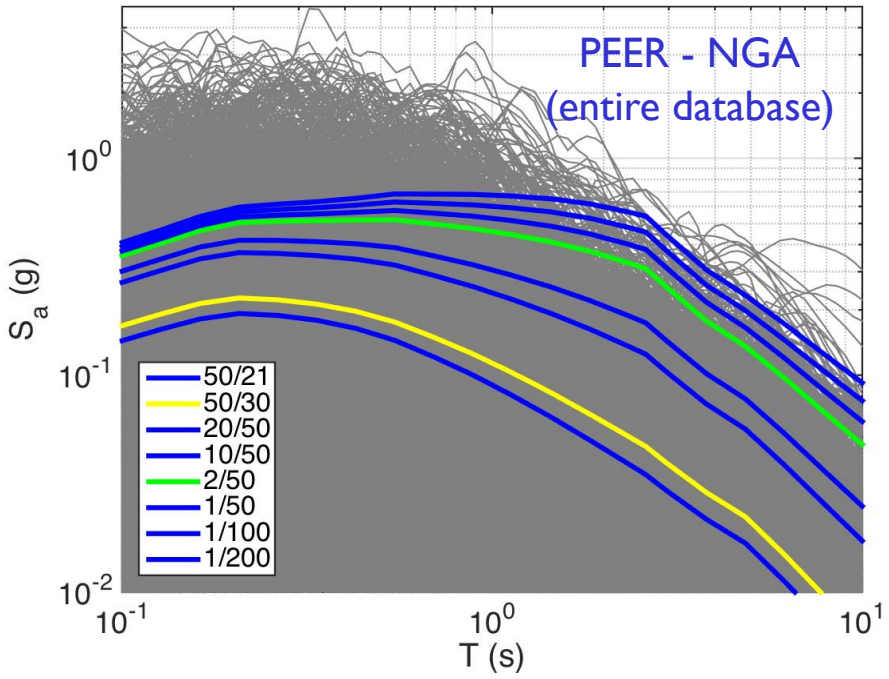
Correlation of Spectra Intensity across Periods

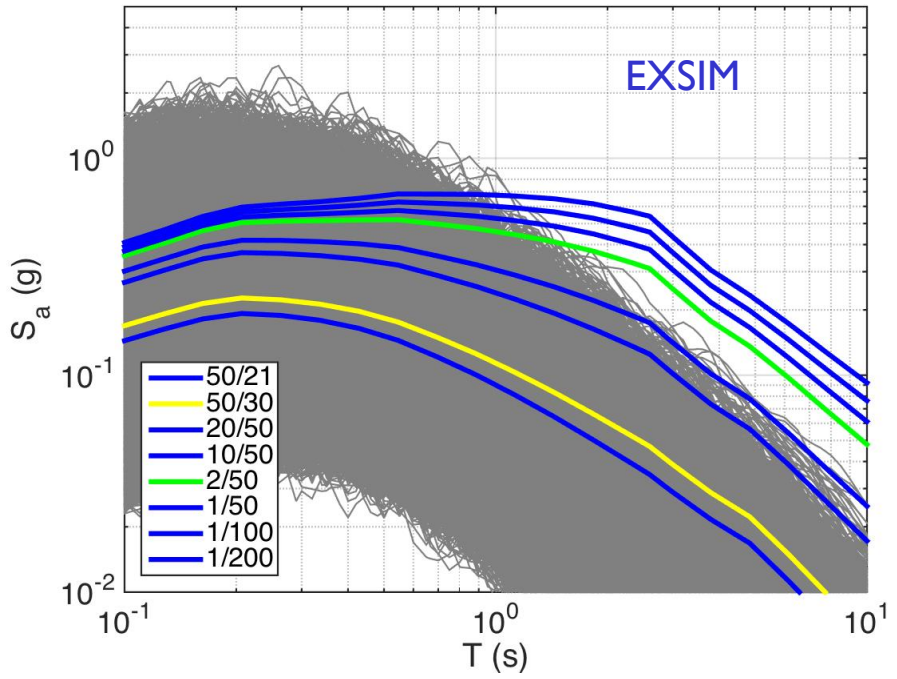
Engineering Application: Similar IM



Engineering Application: Similar Spectra

Extend similar spectra study with ground motions from CyberShake

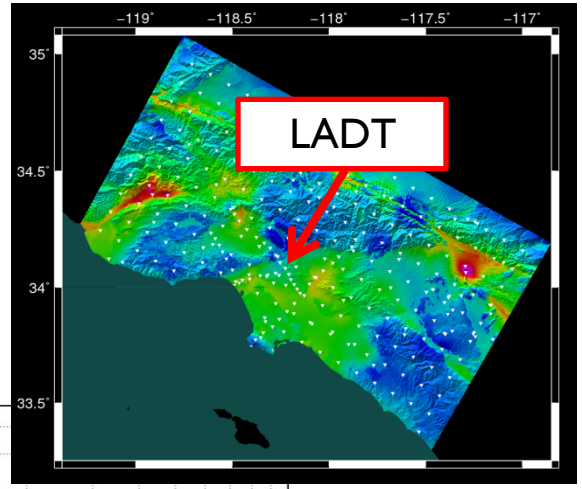


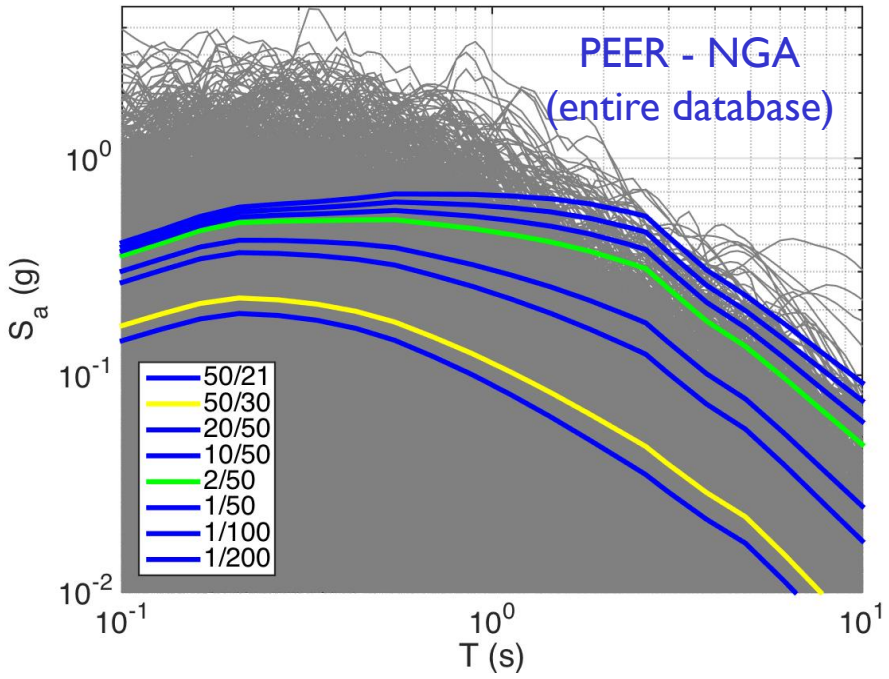


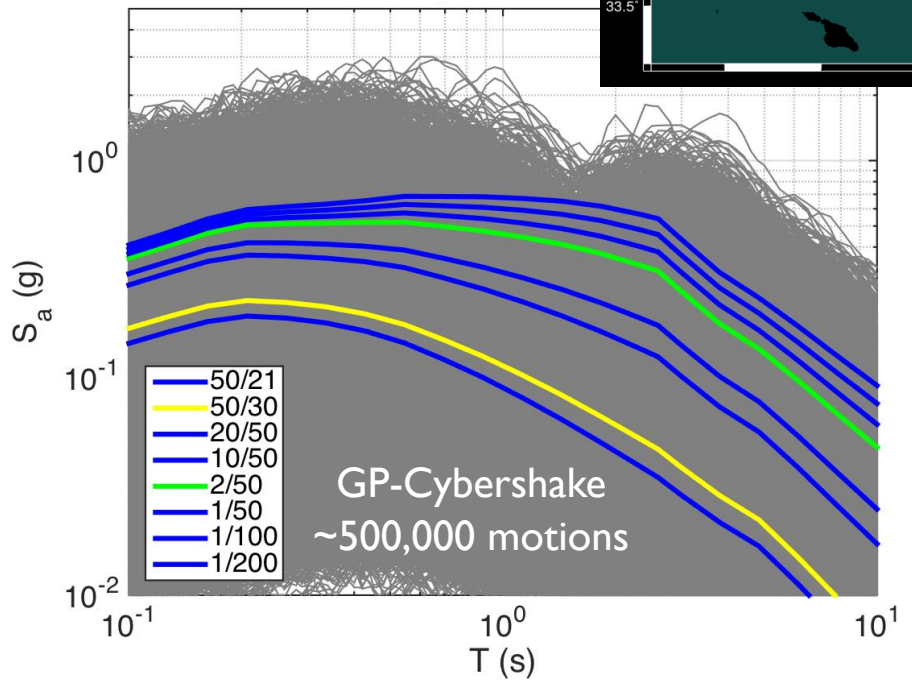
Engineering Application: Similar Spectra

Extend similar spectra study with ground motions from CyberShake

No Record Scaling!

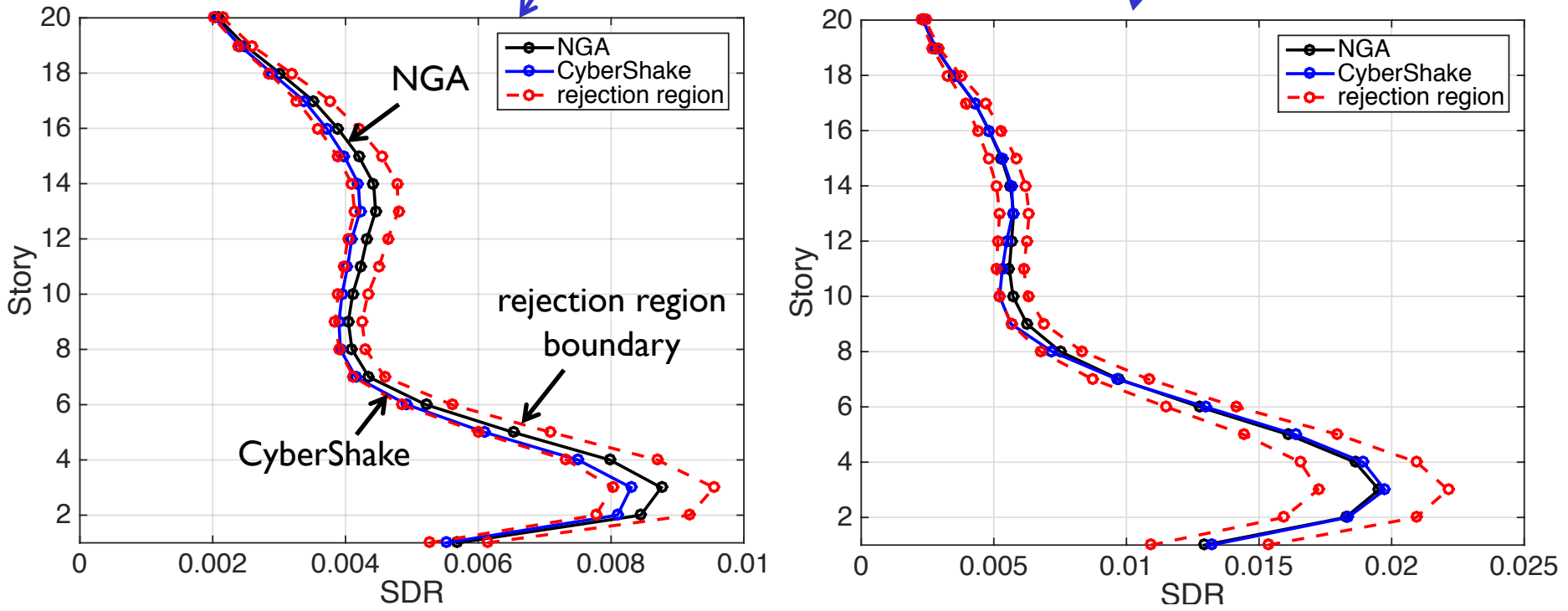






Engineering Application: Similar IM

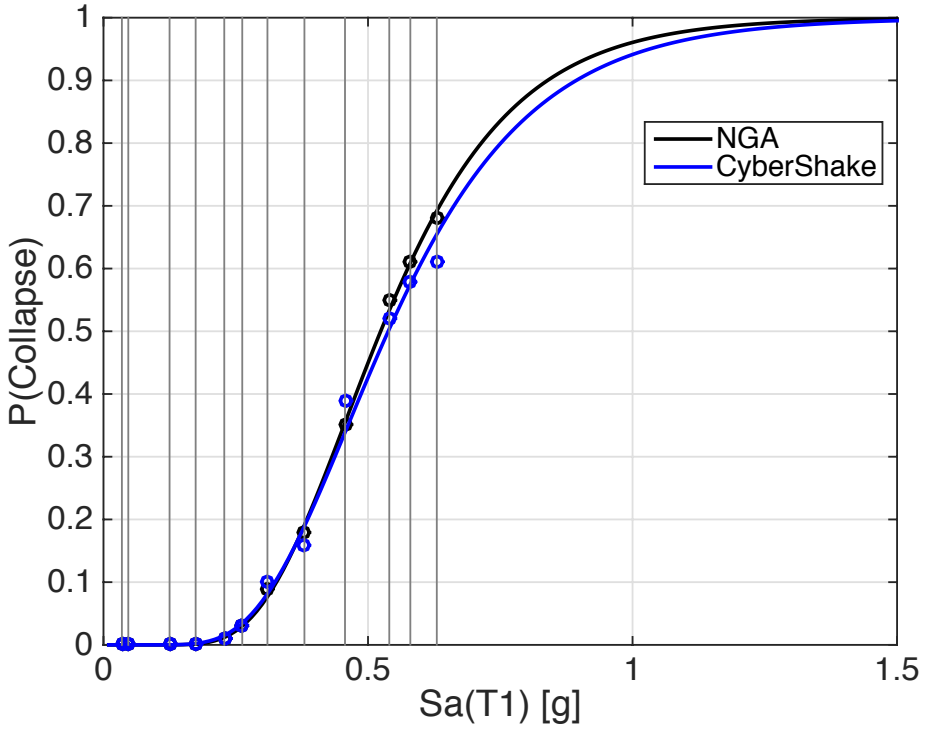
Intensity stripes at which structural responses are compared (San Jose hazard)										
Sa (T=2.6s) [g]	0.03	0.05	0.12	0.17	0.23	0.26	0.31	0.38	0.46	0.54
Intensity level X % / Y years	50/21	50/30	20/50	10/50	5/50	5/75	2/50	1/50	1/100	1/200



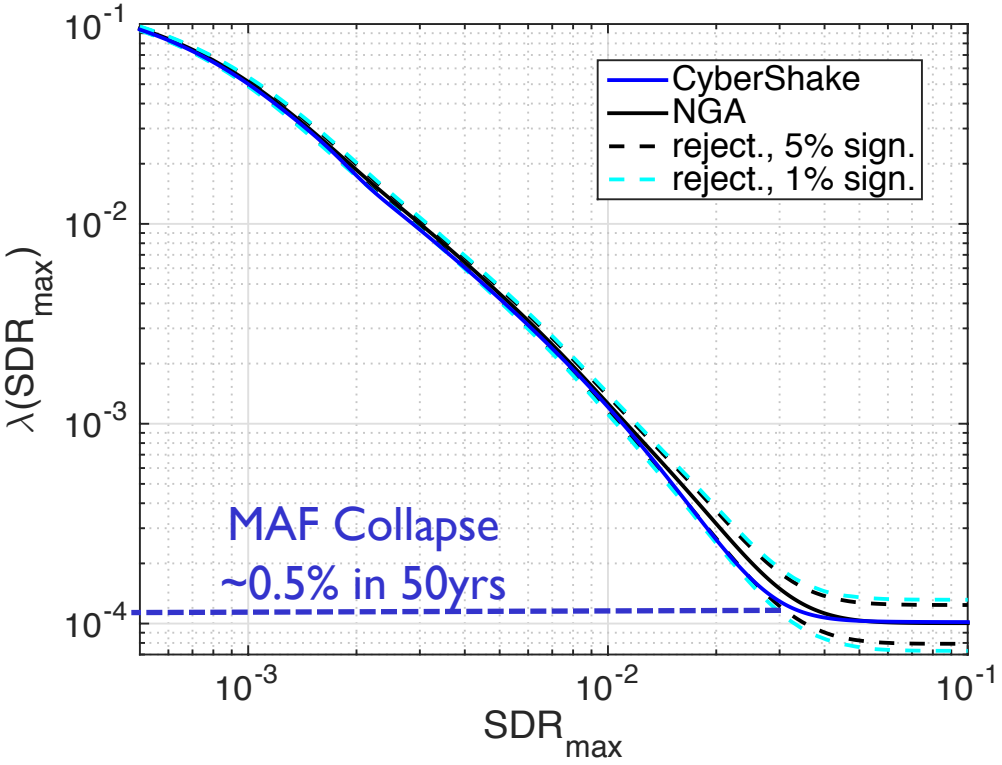
Median Story Drift Ratio (SDR)

Engineering Application: Similar IM

Intensity stripes at which structural responses are compared (San Jose hazard)										
Sa (T=2.6s) [g]	0.03	0.05	0.12	0.17	0.23	0.26	0.31	0.38	0.46	0.54
Intensity level X % / Y years	50/21	50/30	20/50	10/50	5/50	5/75	2/50	1/50	1/100	1/200



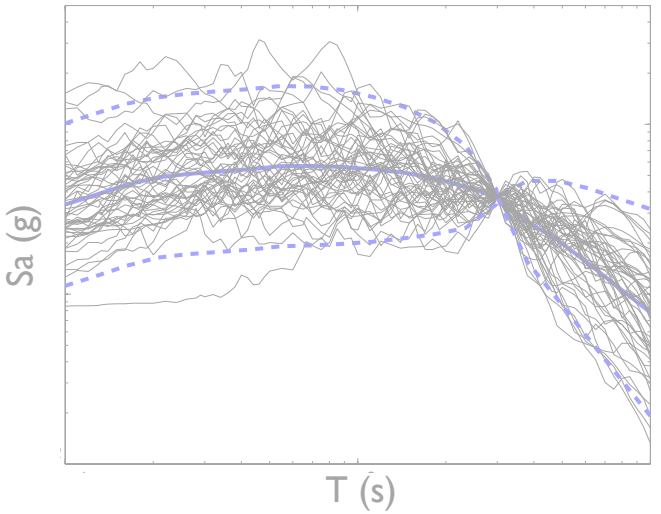
Collapse fragility

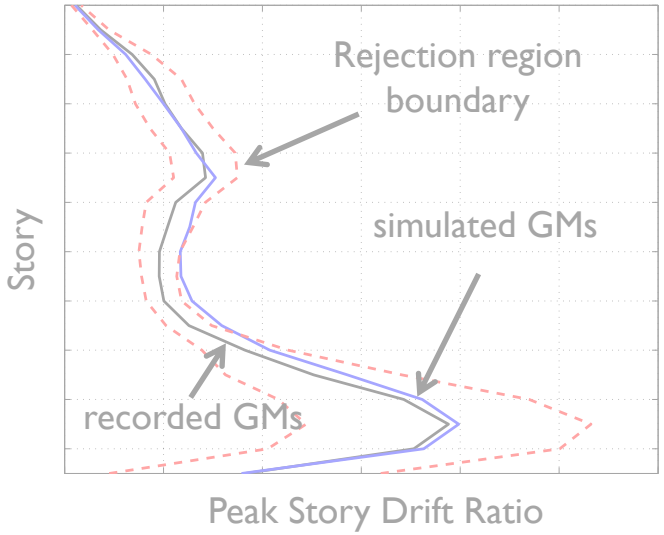


Story drift exceedance

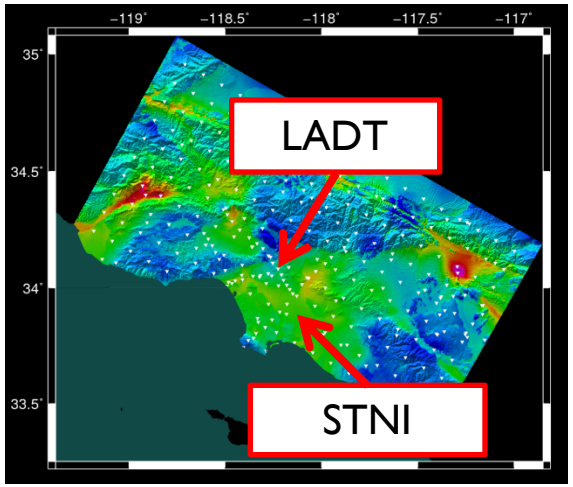
Engineering Applications/Validations with Simulated Motions

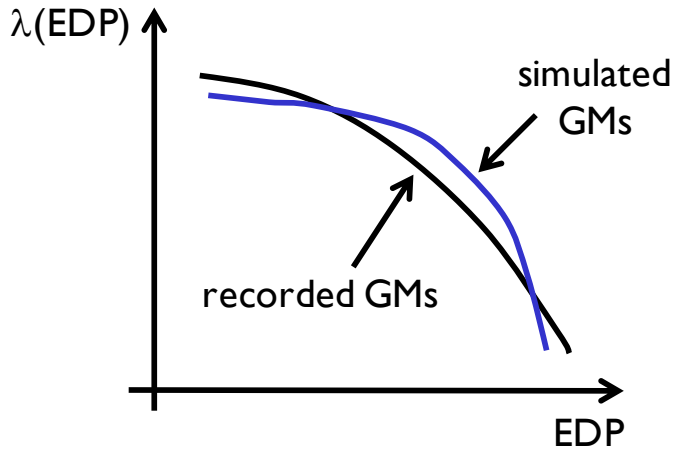
Similar IM Validation



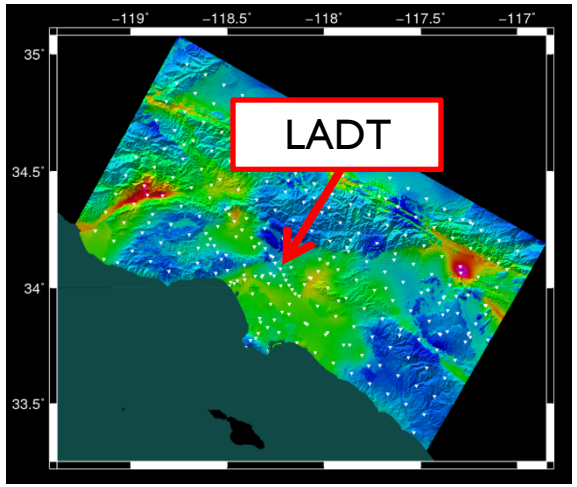


Conventional vs. CyberShake



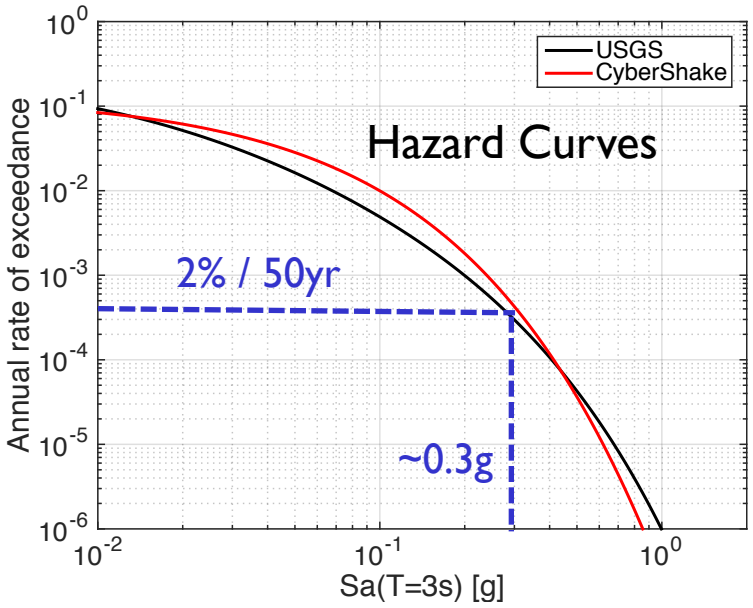


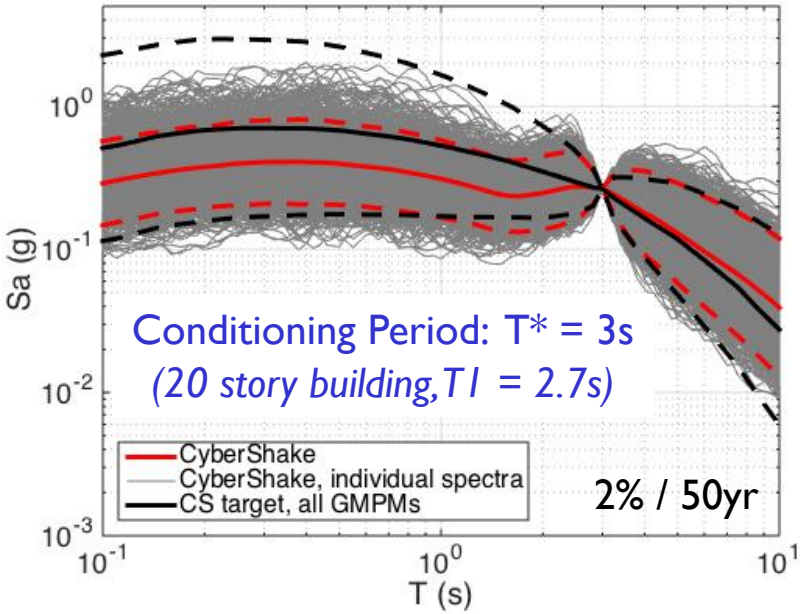
Engineering Application: Direct Simulation (CyberShake)

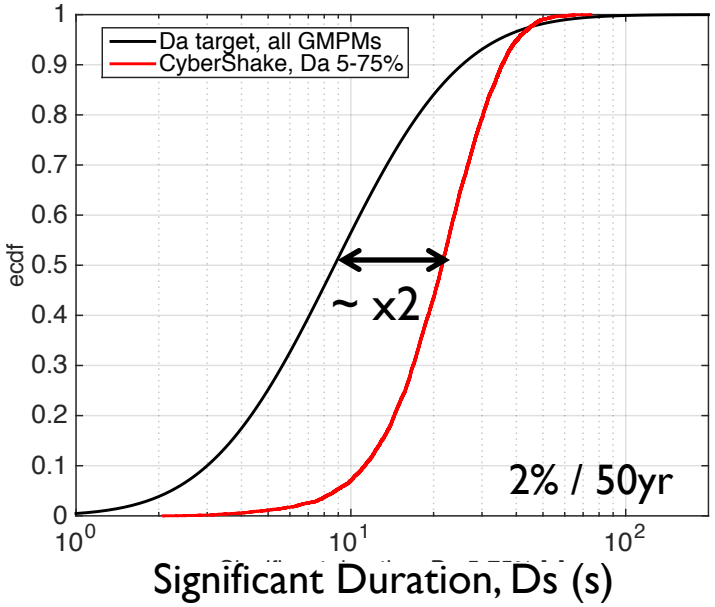


Comparison – CyberShake and Conventional PSHA

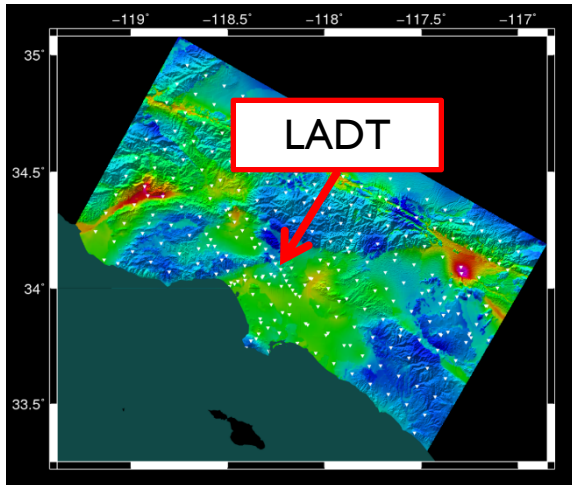
- hazard curve *(Sa for T = 3s)*
- ground motion CS *(Sa, T* = 3s, multiple return periods)*
- ground motion Ds *(multiple return periods)*

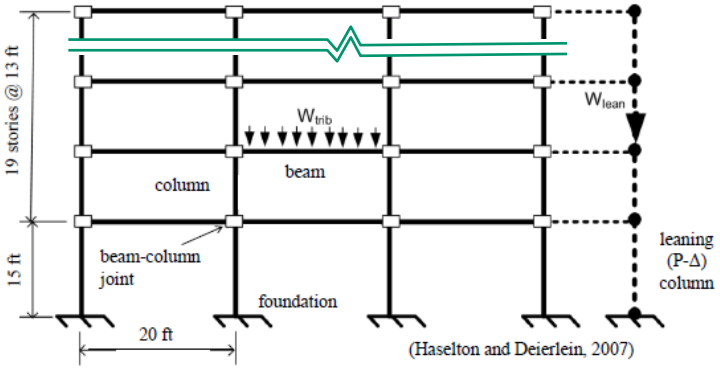






Engineering Application: Direct Simulation (CyberShake)

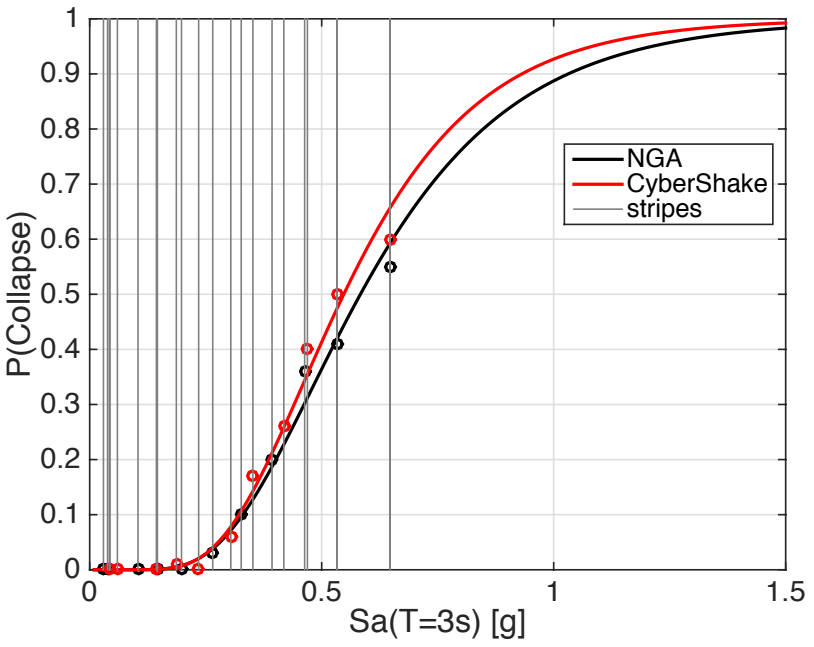




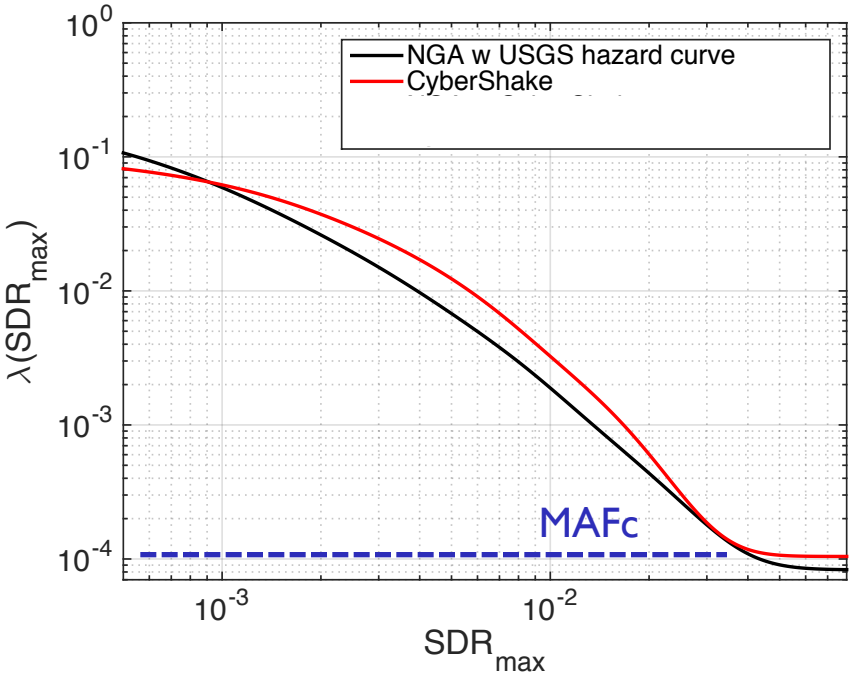
20-story building, T_1 = 2.60s

Structural Response Comparisons

- Collapse – conditioned on Sa(T*)
- Story Drift – mean annual frequency of exceedence

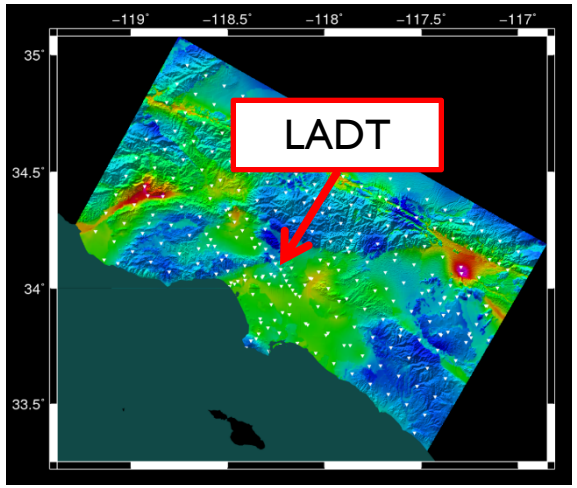


Collapse Fragility



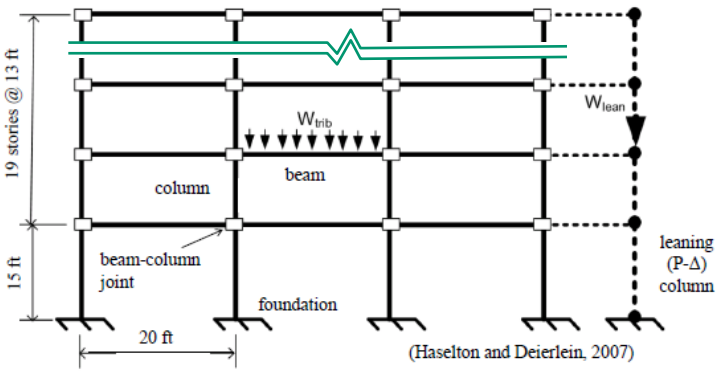
Story Drift Exceedence

Engineering Application: Direct Simulation (CyberShake)

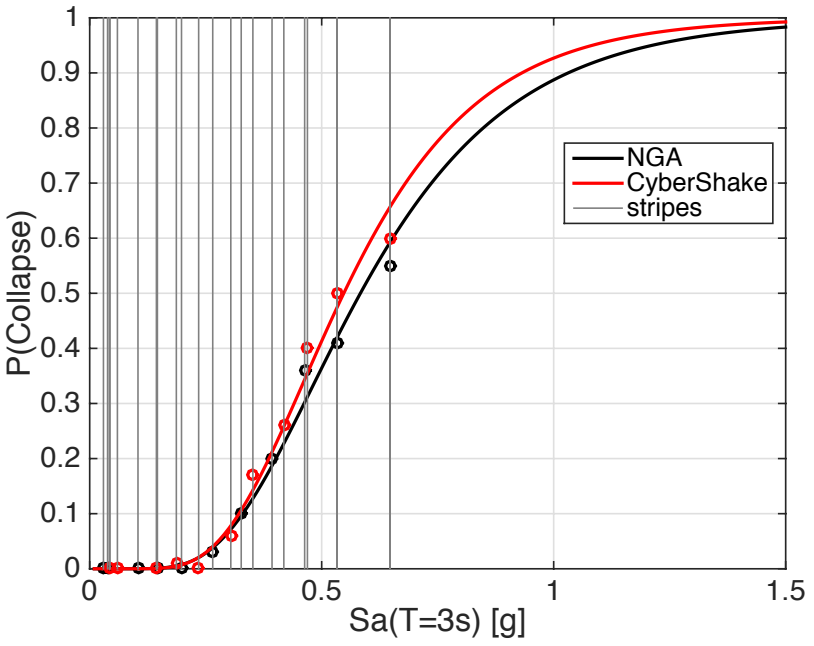


Mix and Match: ground motions with hazard curves

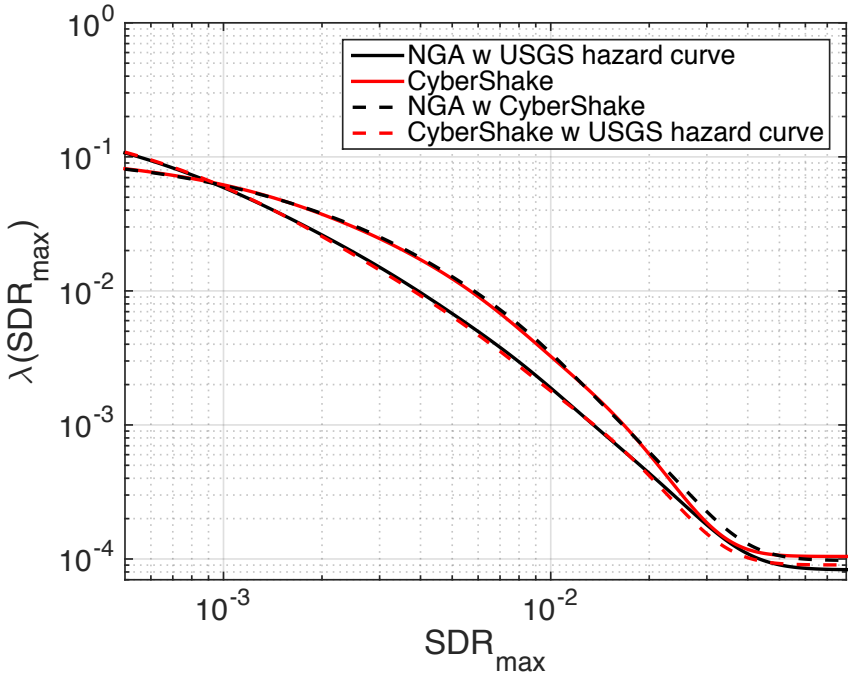
Observation: difference in drift exceedence is attributed primarily to differences in hazard curve



20-story building, T_1 = 2.60s

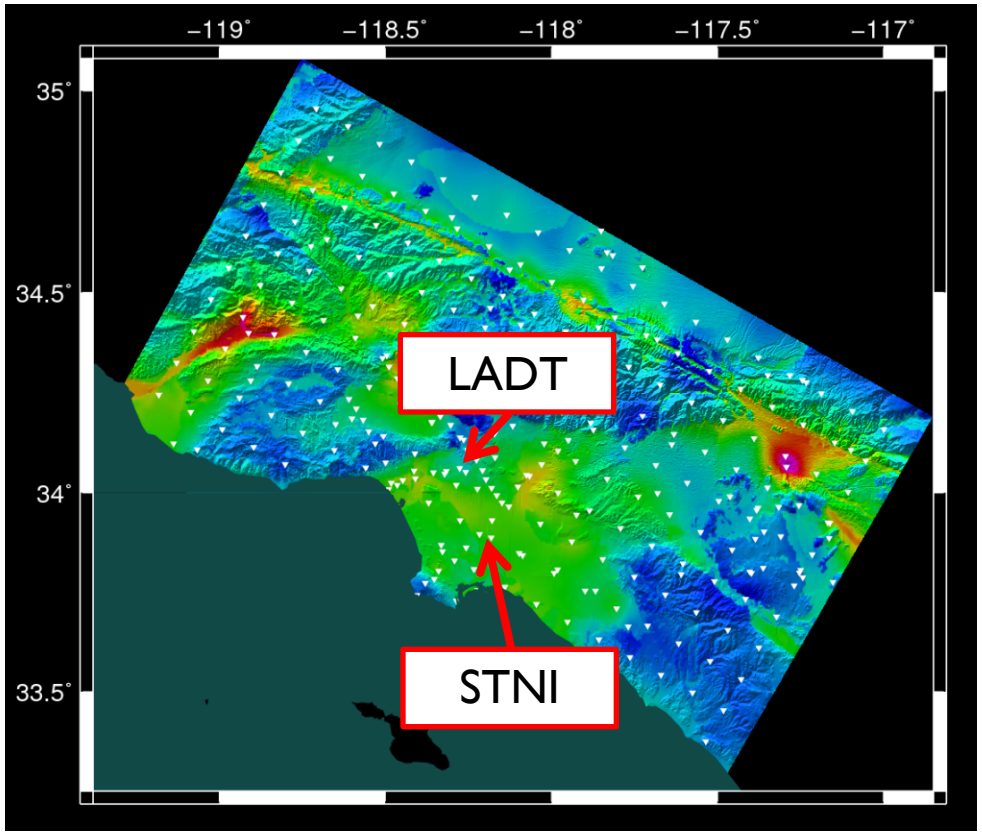


Collapse Fragility



Story Drift Exceedence

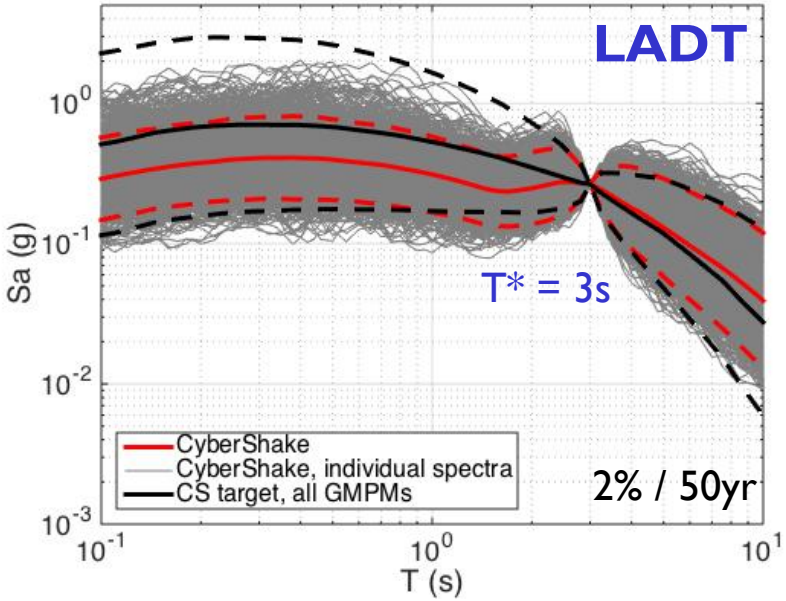
Engineering Application: Direct Simulation (CyberShake)

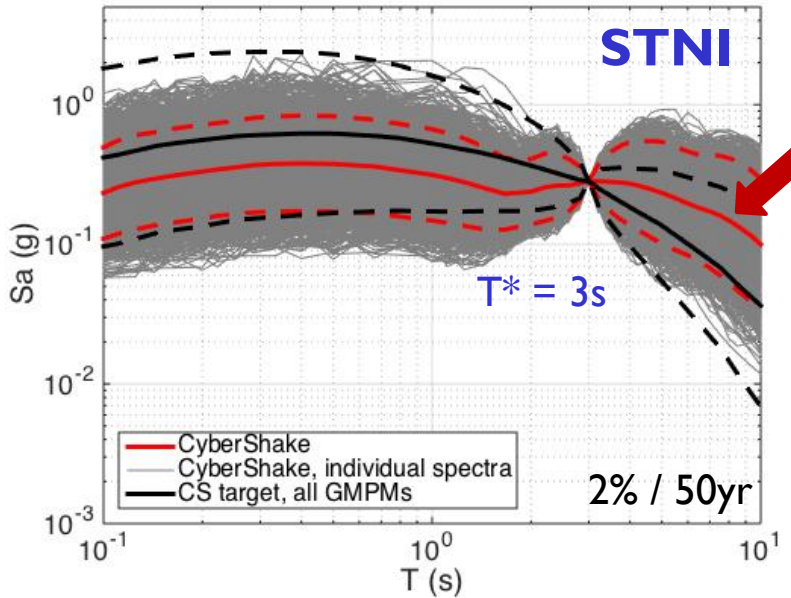


Deep Basin Site

LADT: V_{s30} = 390 m/s; $Z_{1.0}$ = 0.3 km

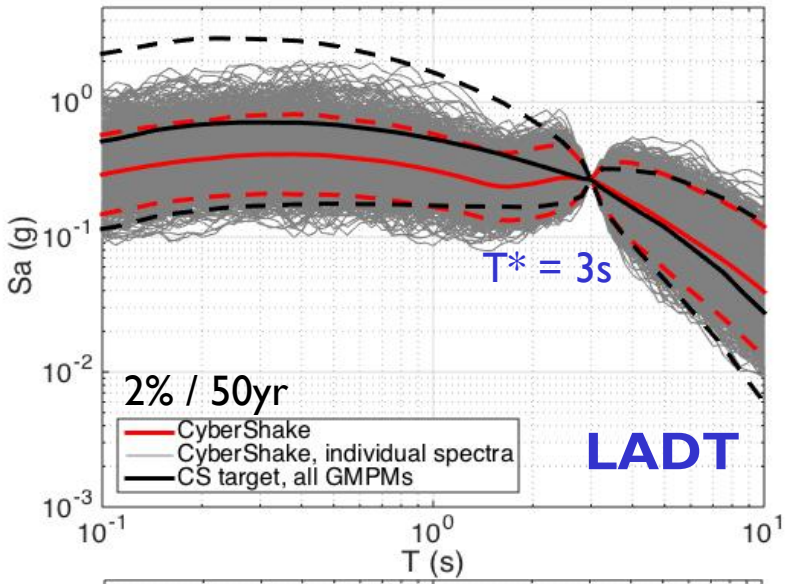
STNI: V_{s30} = 280 m/s; $Z_{1.0}$ = 0.9 km

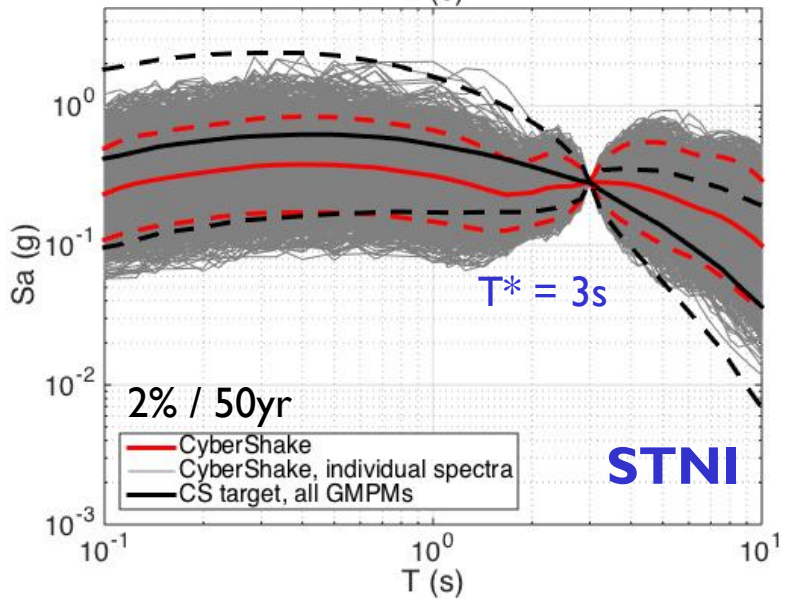


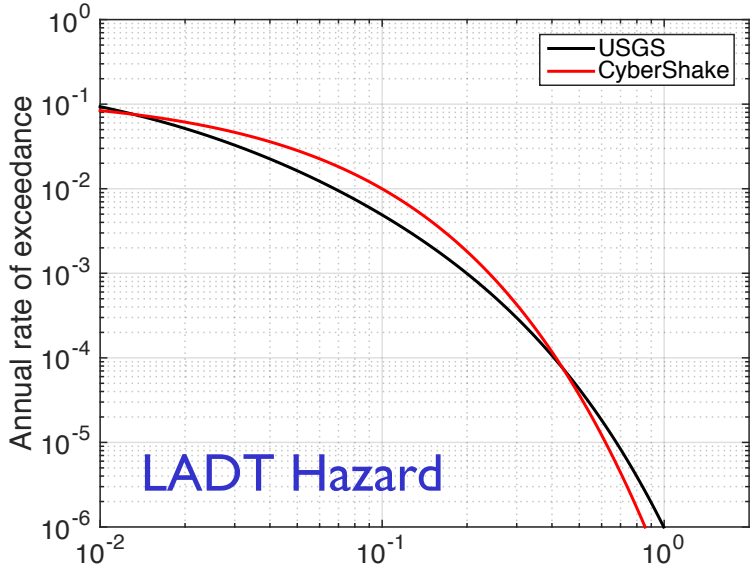


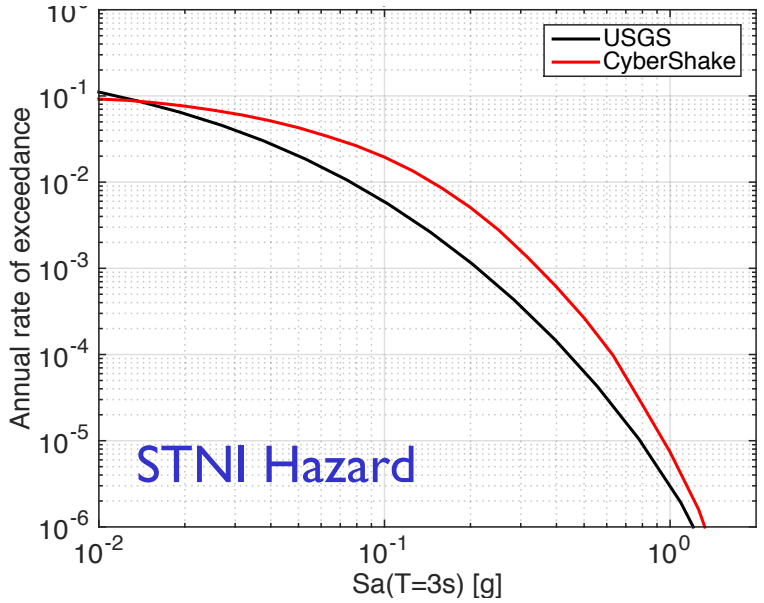
more damaging spectra than CS target

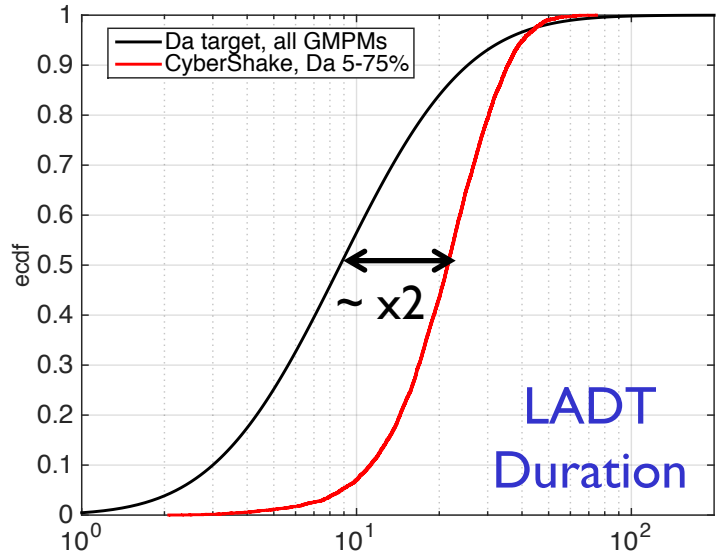
Engineering Application: Direct Simulation (CyberShake)

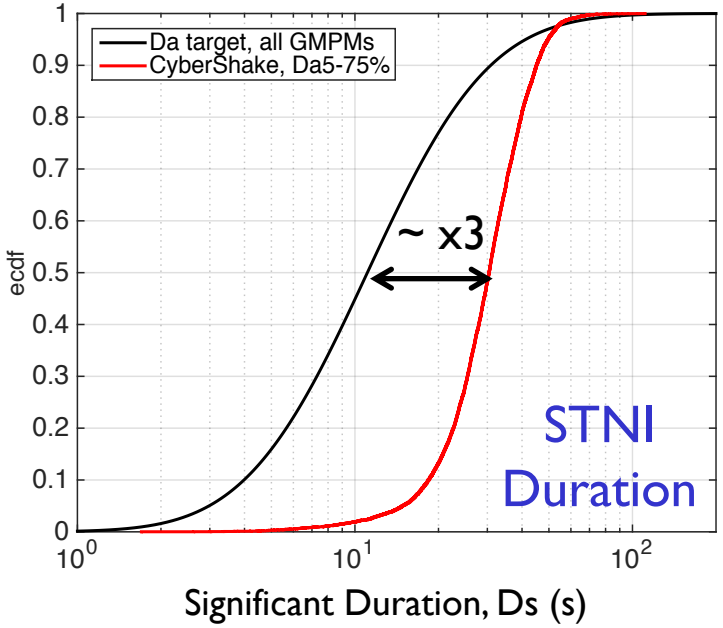




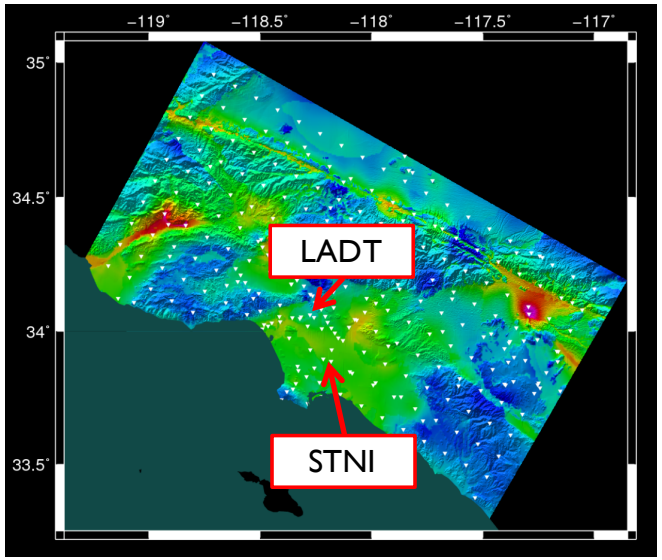


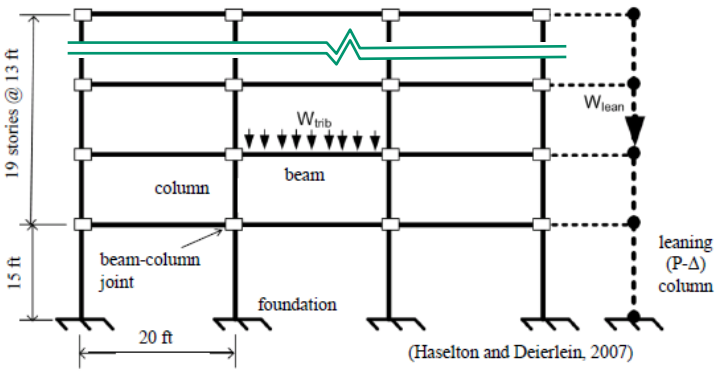




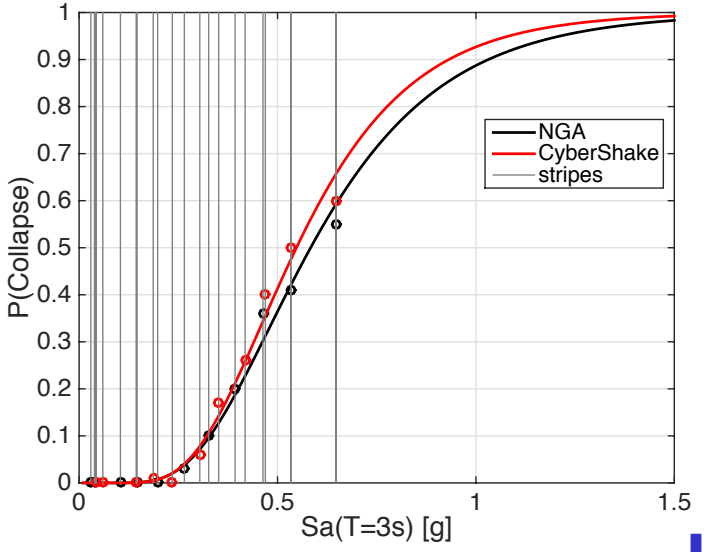


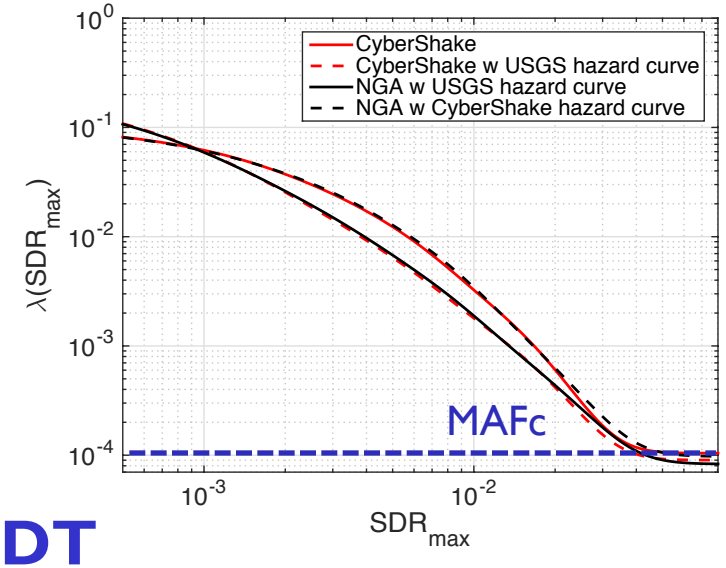
Engineering Application: Direct Simulation (CyberShake)



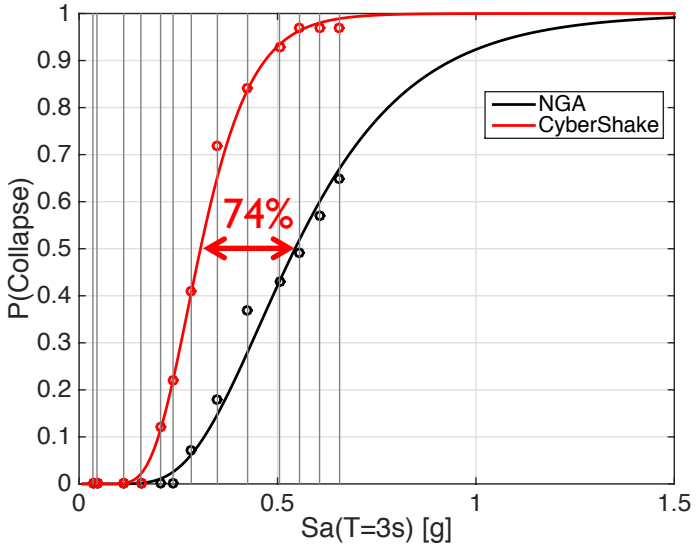


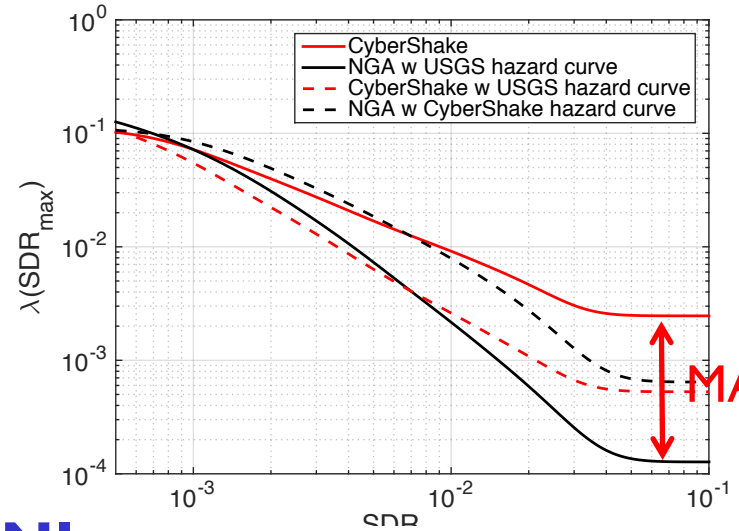
20-story building, T_1 = 2.60s





LADT



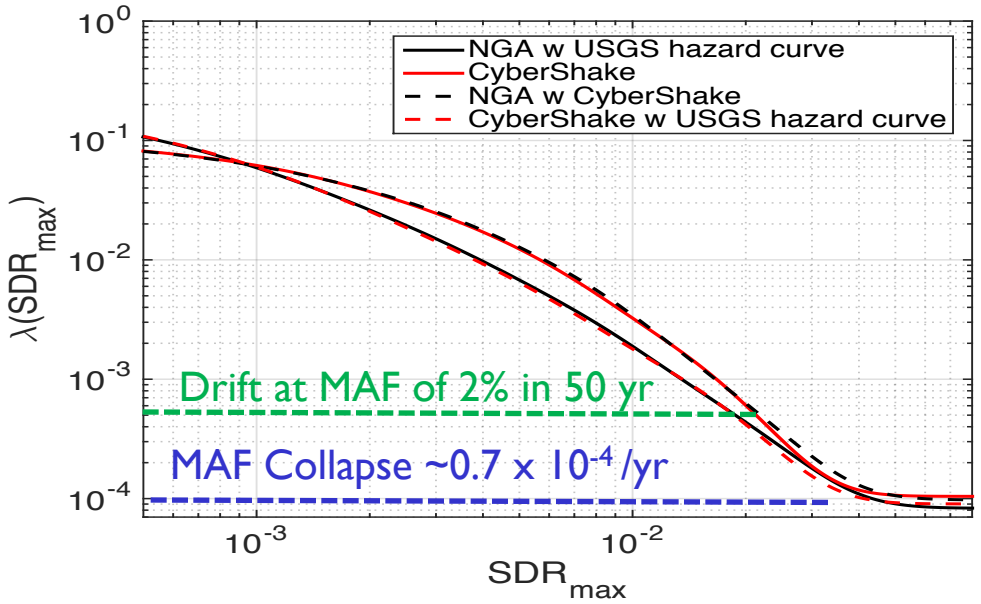


STNI

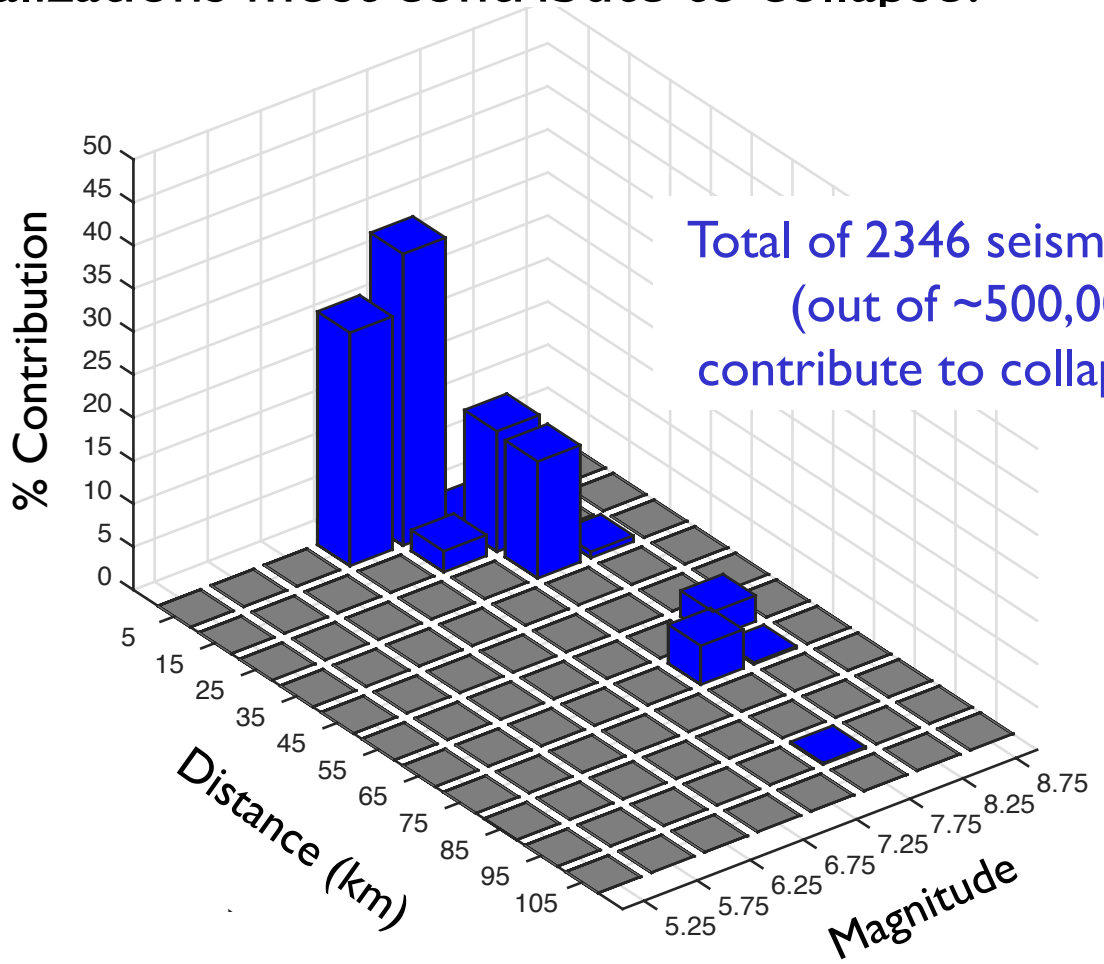
Collapse Fragility

Story Drift Exceedence

Engineering Application: Direct Simulation (CyberShake)

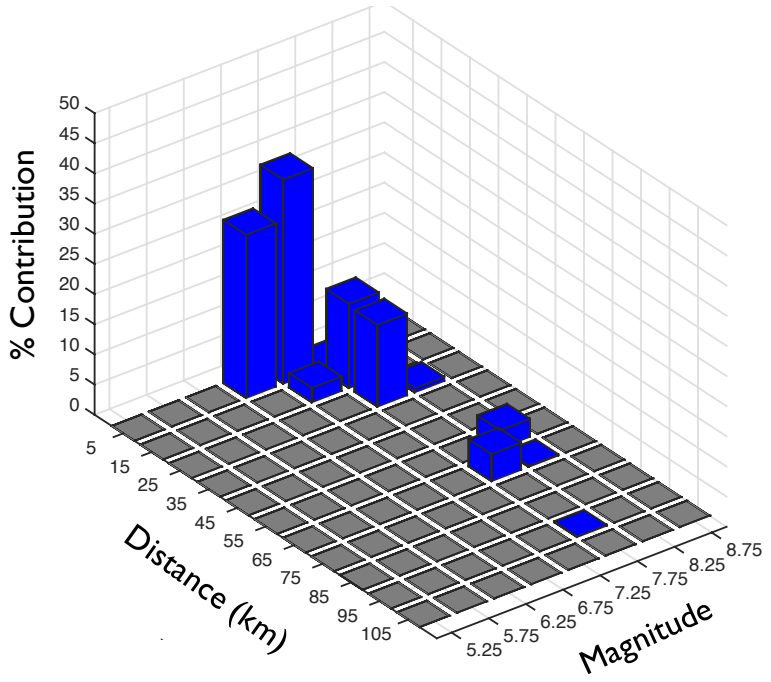


Deaggregation of Risk:
Which earthquake faults and rupture realizations most contribute to collapse?

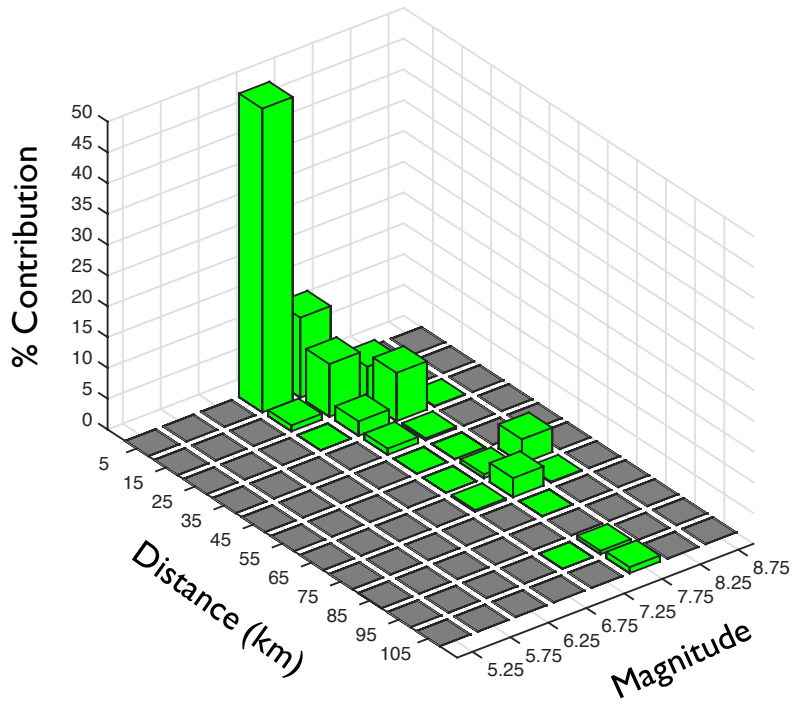


Total of 2346 seismographs (out of ~500,000) contribute to collapse risk

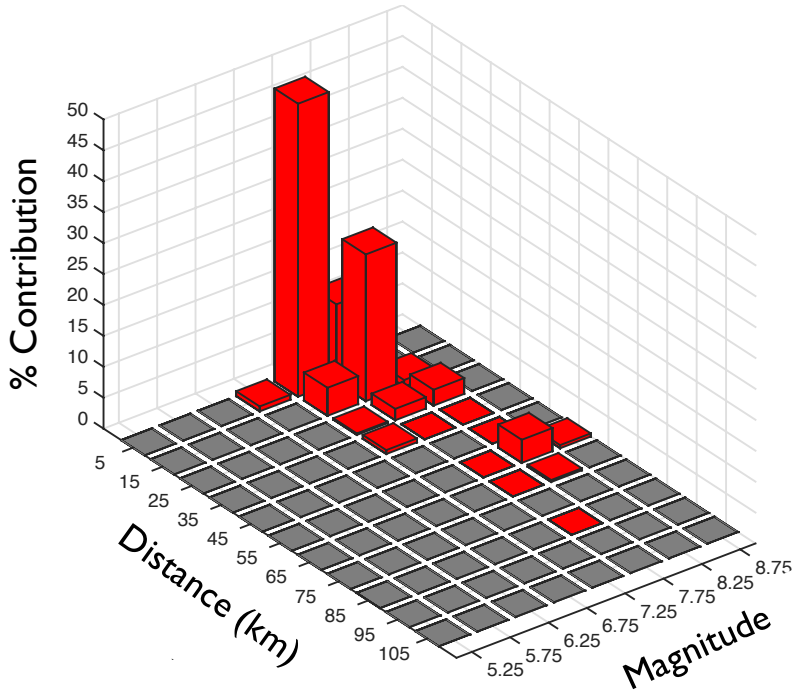
Engineering Application: Direct Simulation (CyberShake)



MAF Collapse
(0.3% in 50 yr)



Story Drift Exceedence
(0.023 drift @ 2% in 50 yr)

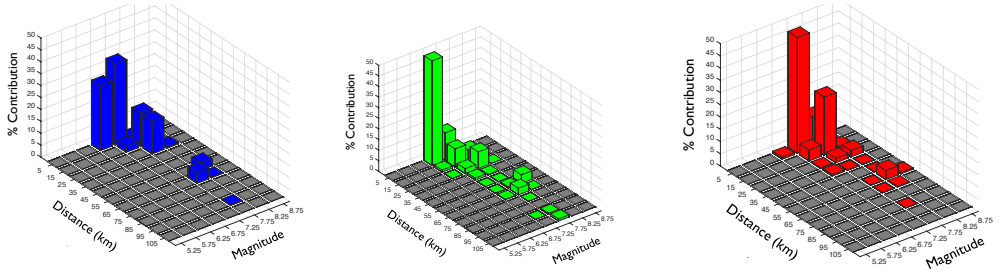


Sa(T=3s) Exceedence
(0.3g @ 2% in 50 yr)

Risk Deaggregation

Hazard Deaggregation

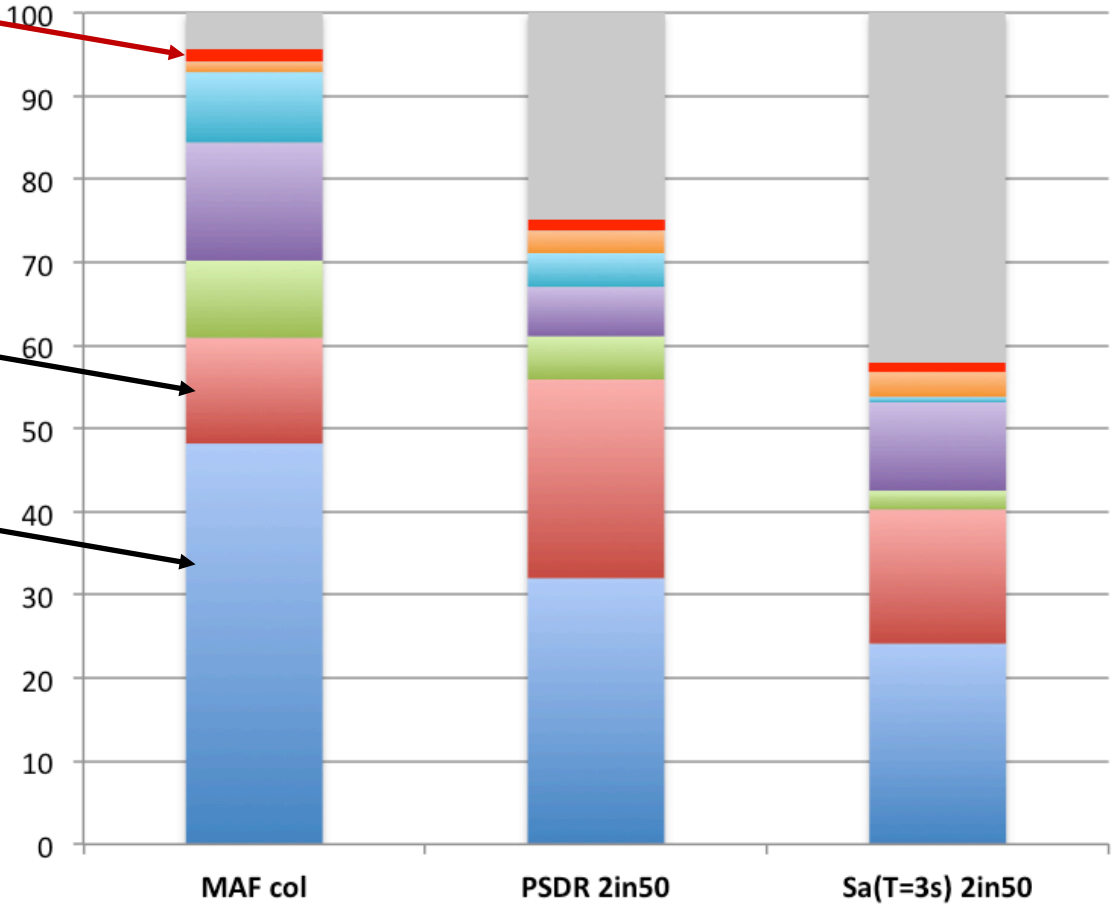
Engineering Application: Direct Simulation (CyberShake)



San Andreas

Raymond

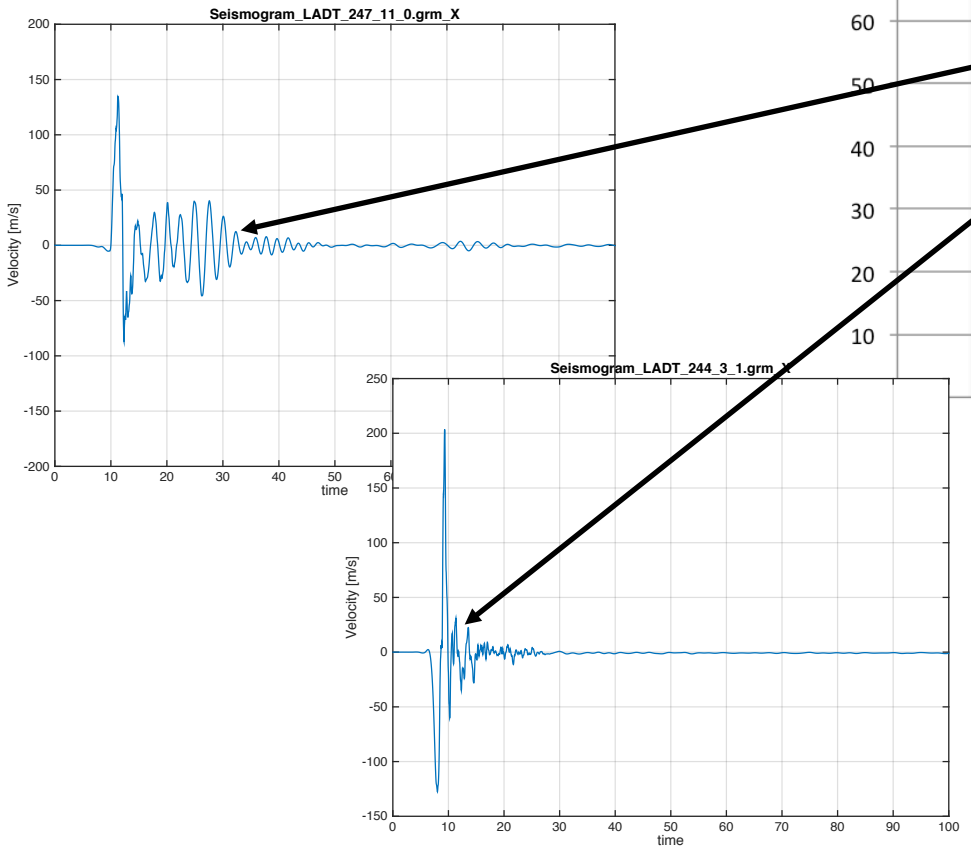
Puente Hills

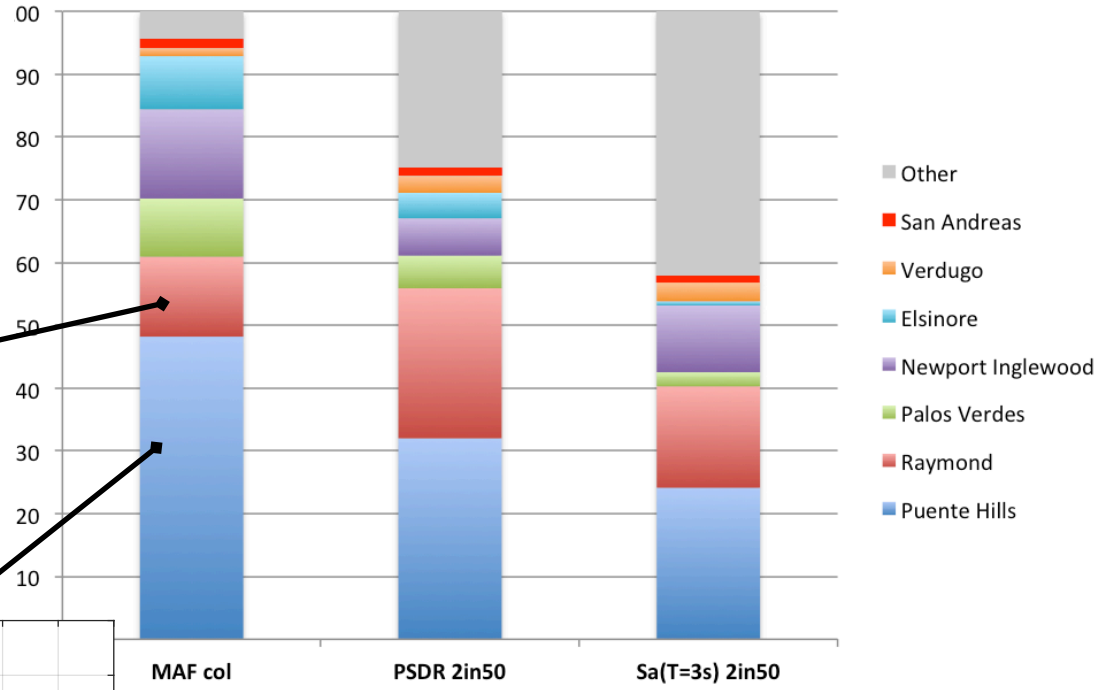


- Other
- San Andreas
- Verdugo
- Elsinore
- Newport Inglewood
- Palos Verdes
- Raymond
- Puente Hills

Engineering Application: Direct Simulation (CyberShake)

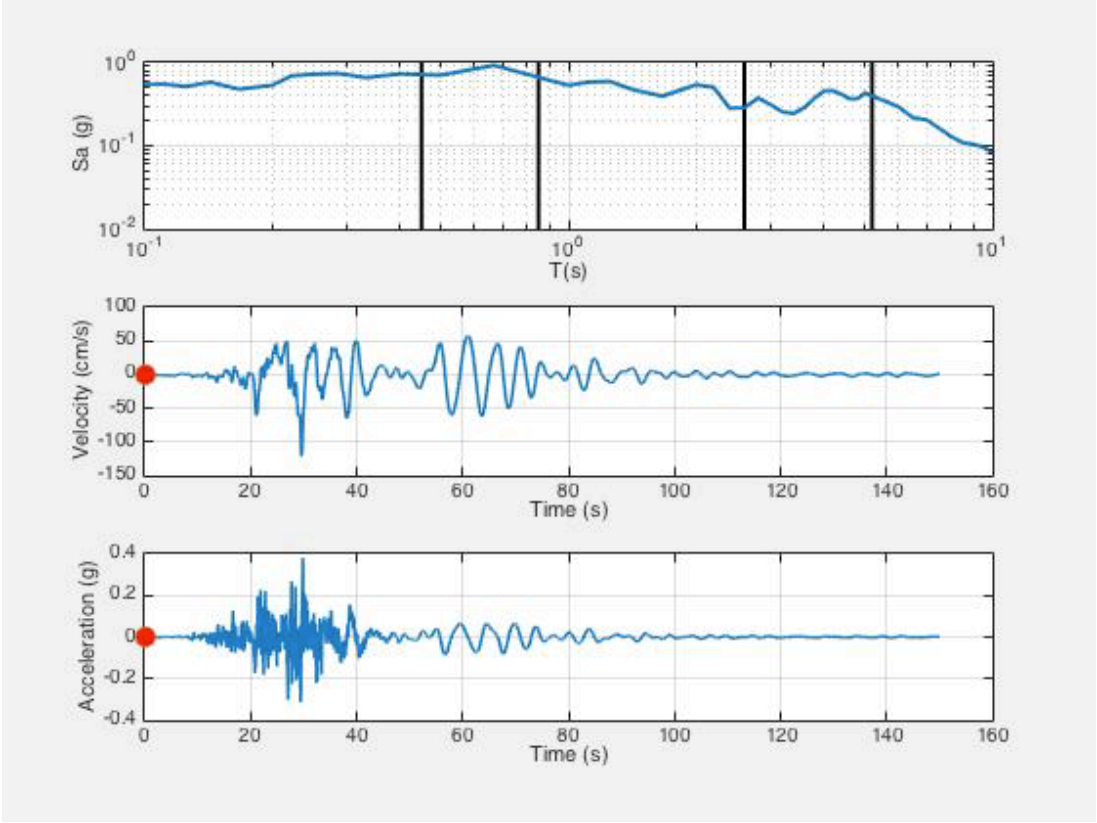
What are the characteristics of the ground motions generated by the faults that contribute to collapse?

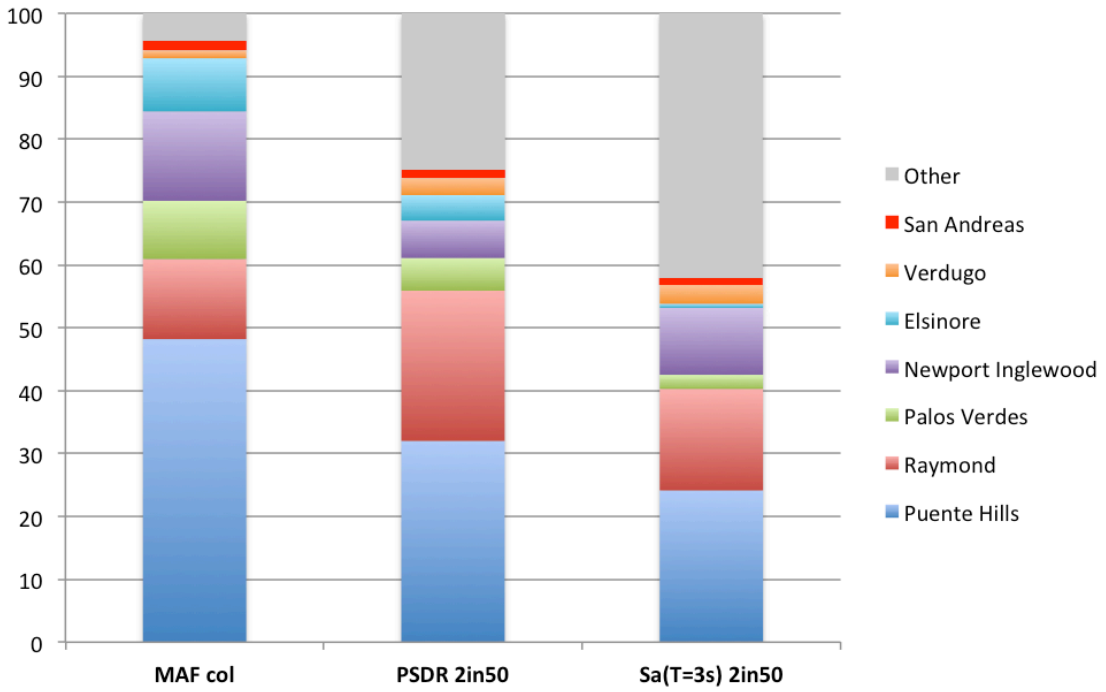




Engineering Application: Direct Simulation (CyberShake)

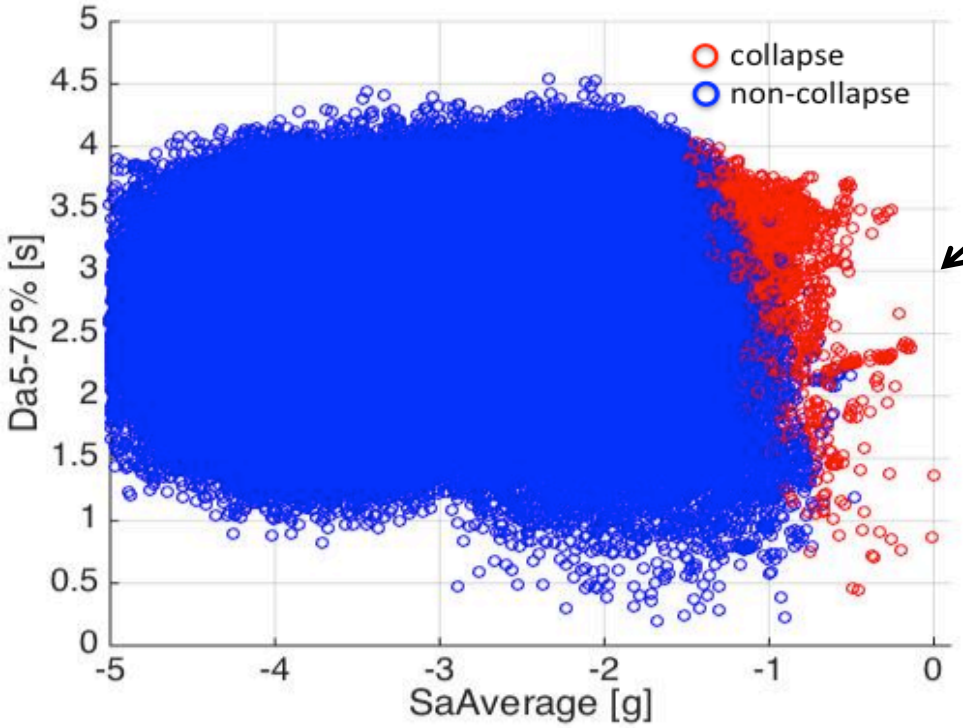
What are the characteristics of the ground motions generated by the faults that contribute to collapse?

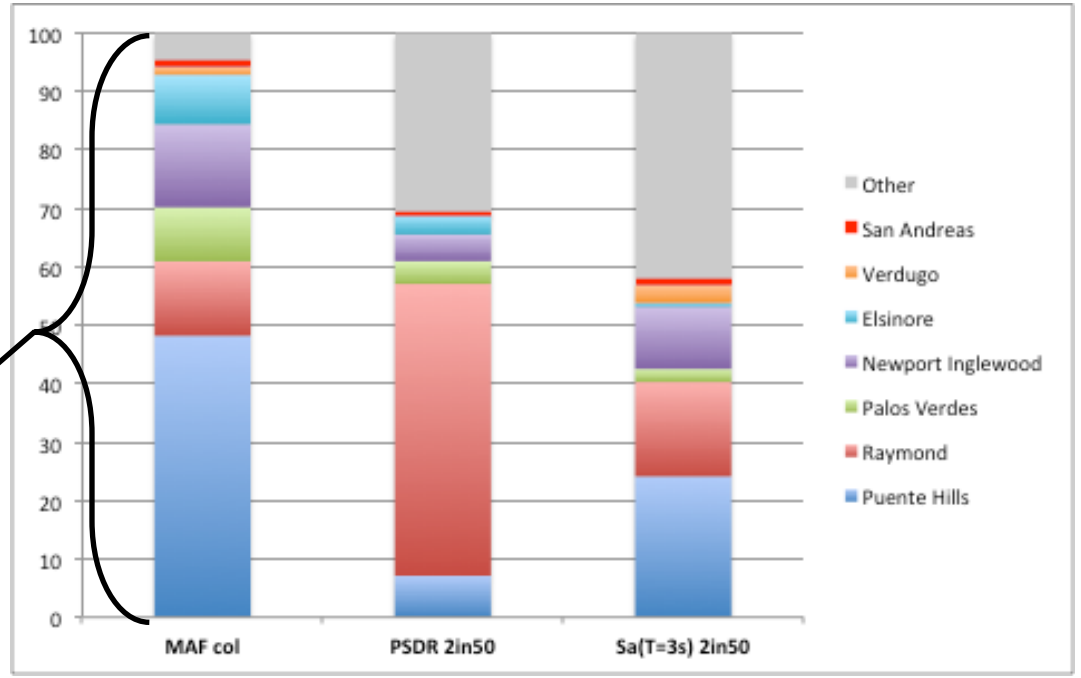




Engineering Application: Direct Simulation (CyberShake)

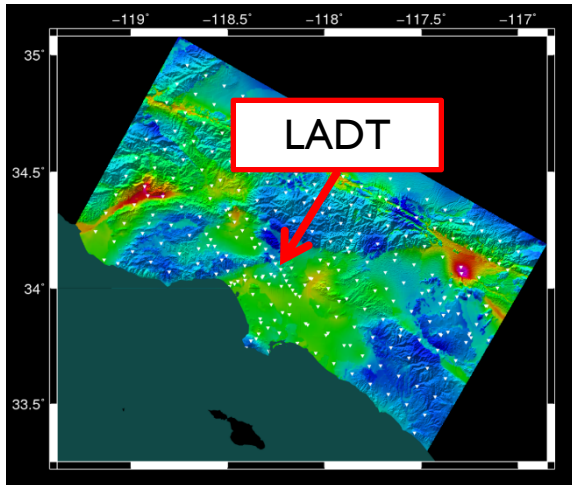
What are the characteristics *(intensity measures)* of the ground motions that contribute to collapse?

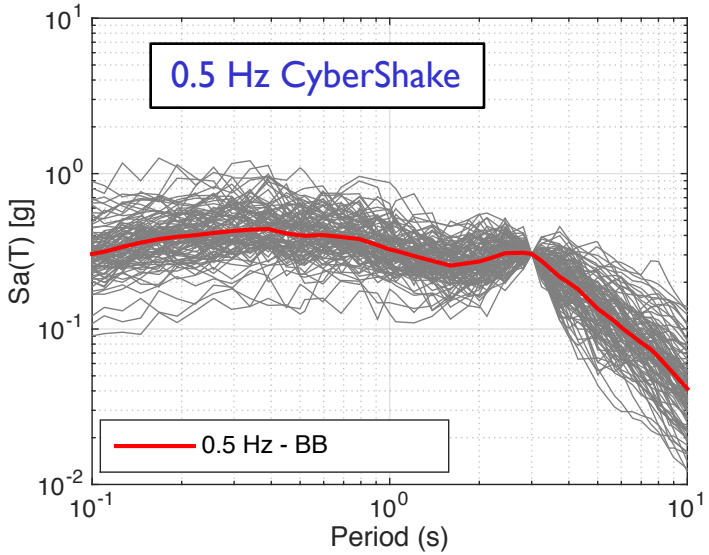


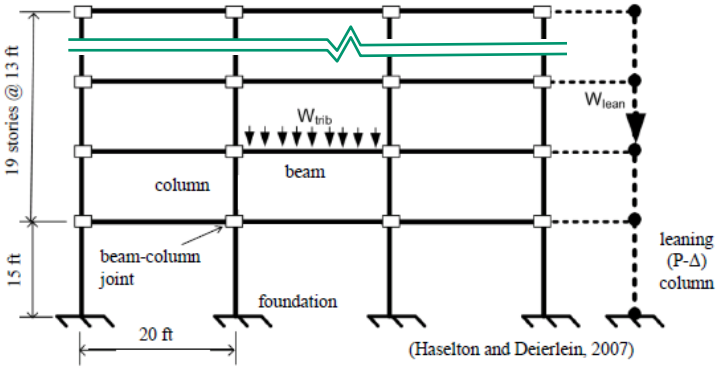


Opportunities to utilize machine learning techniques to interrogate **large *site specific* data sets**, identify damaging ground motion characteristics, and relate them to features of the geology and EQ simulation.

Sensitivity of Response to High Frequency in Ground Motions





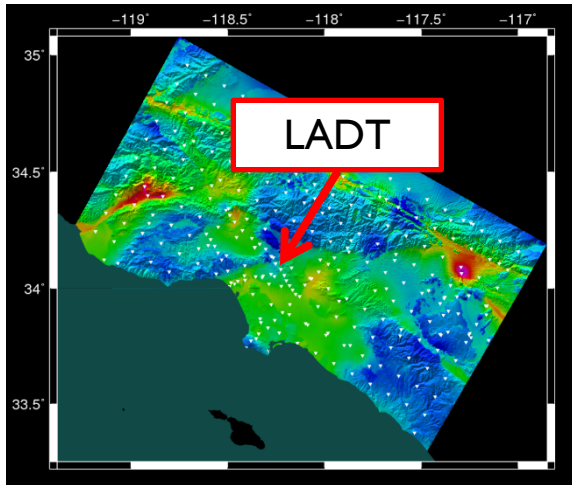


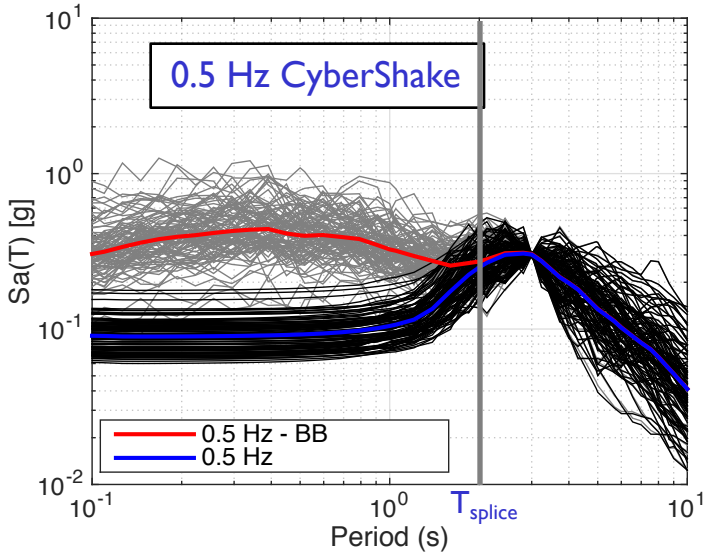
20-story building, T_1 = 2.60s

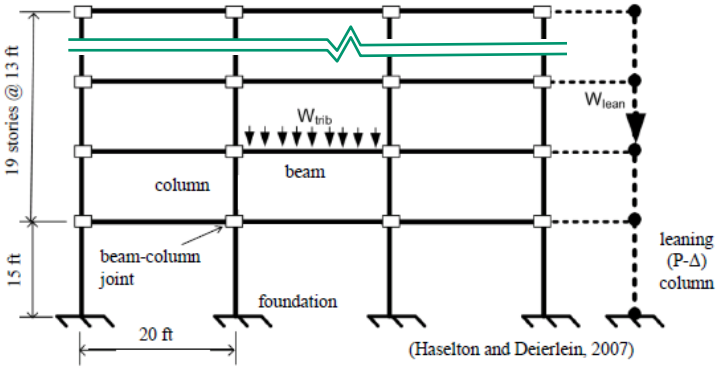
Sensitivity of 20-story Building Response to:

- high frequency of deterministic simulation (0.5Hz vs 1.0Hz)
- broadband (stochastic) component

Sensitivity of Response to High Frequency in Ground Motions







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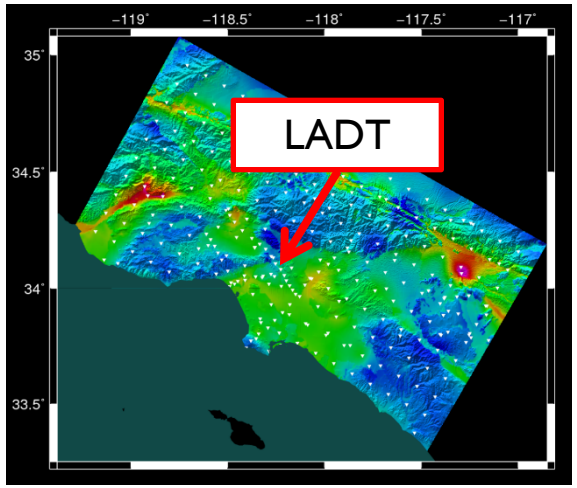

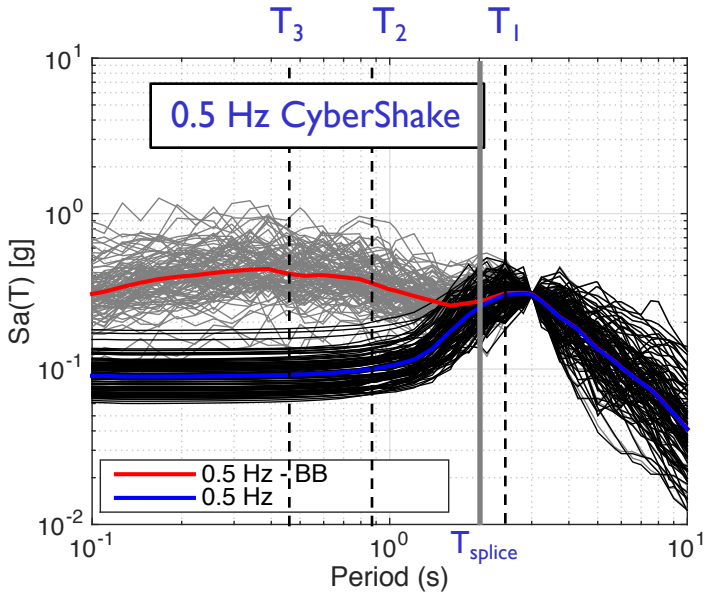

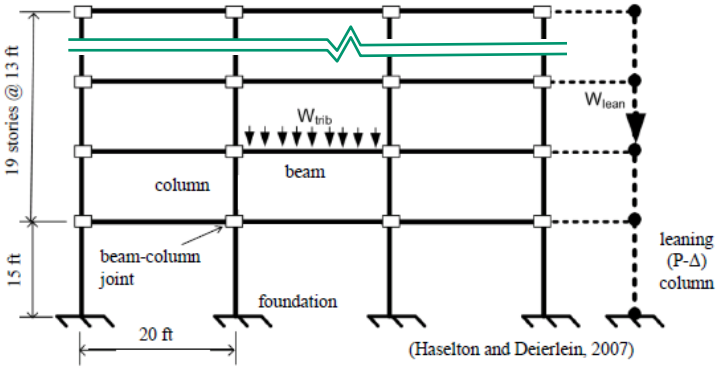

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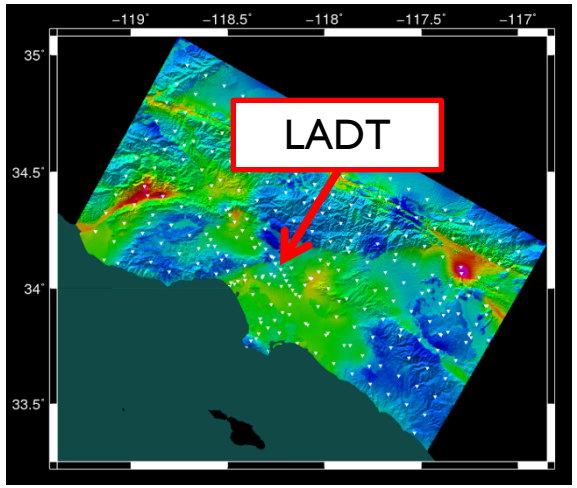

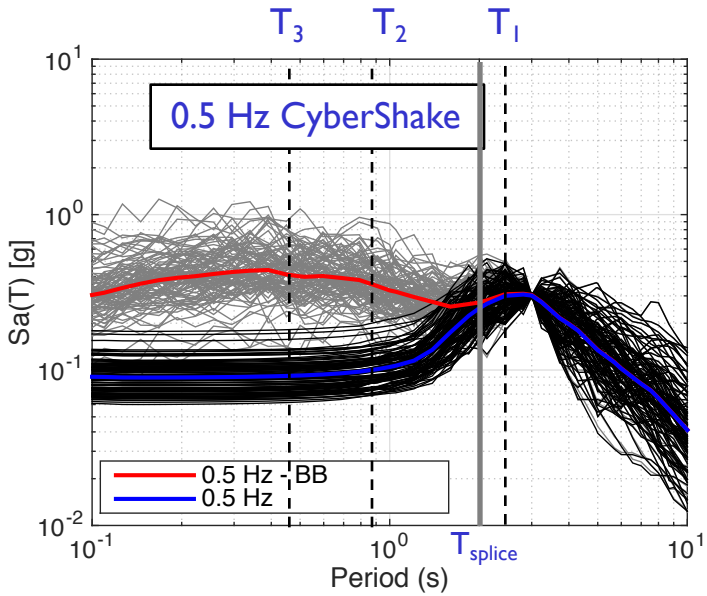

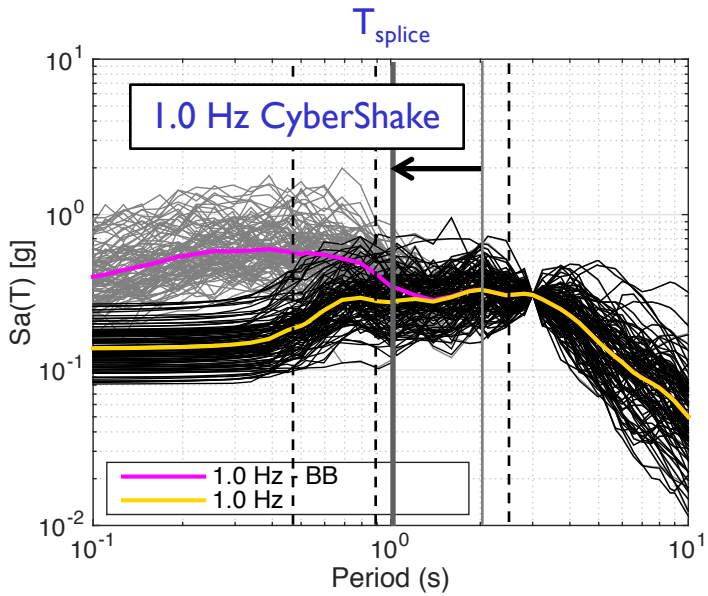

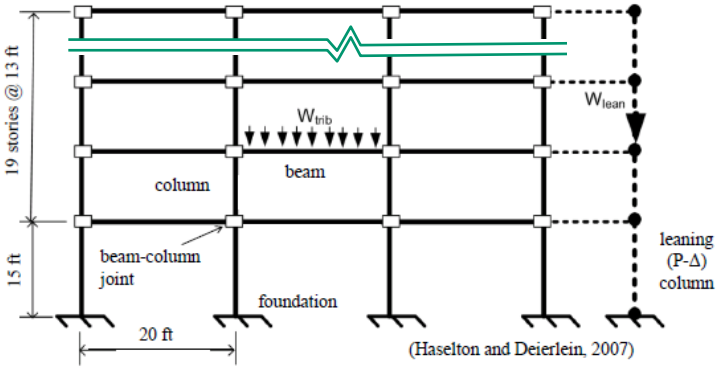

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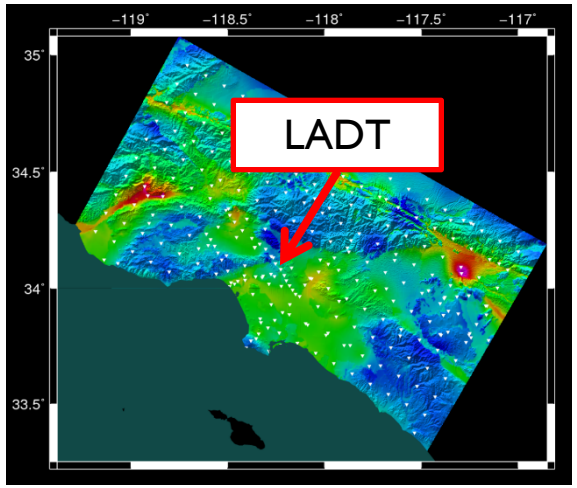
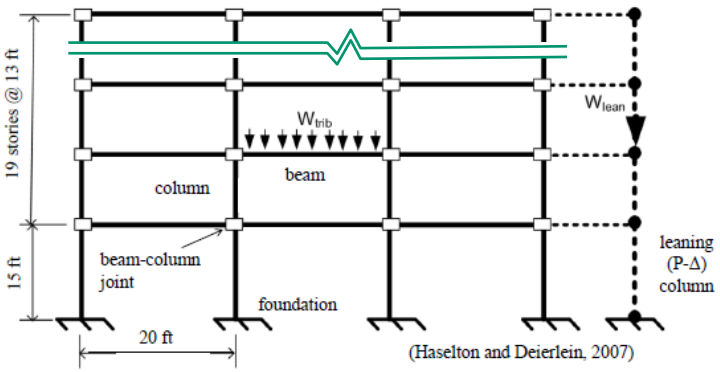
Sensitivity of Response to High Frequency in Ground Motions





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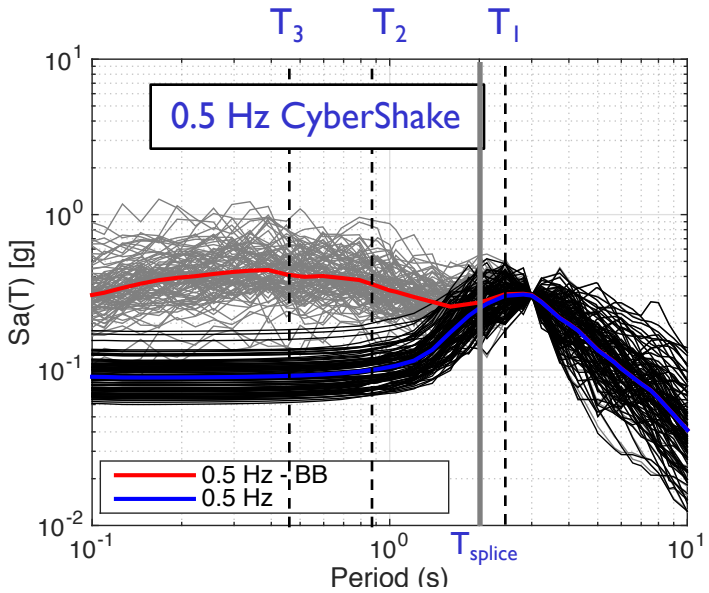
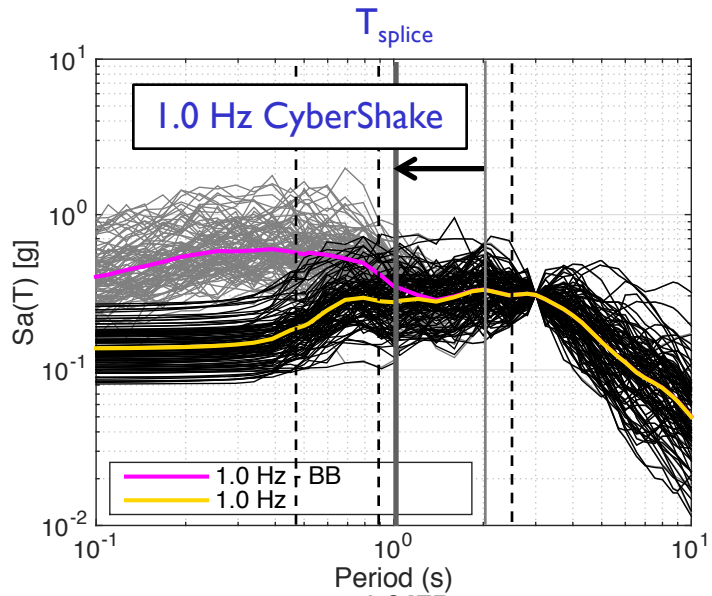
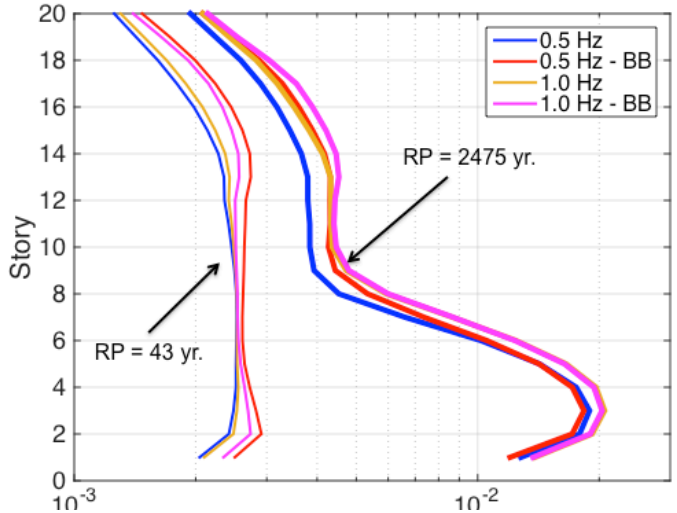
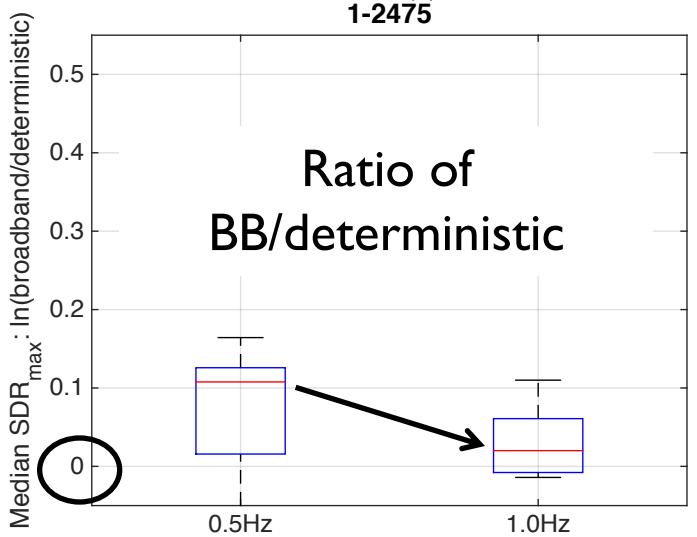


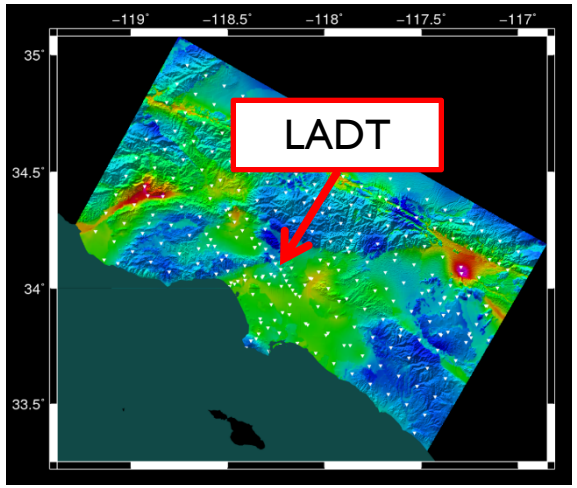


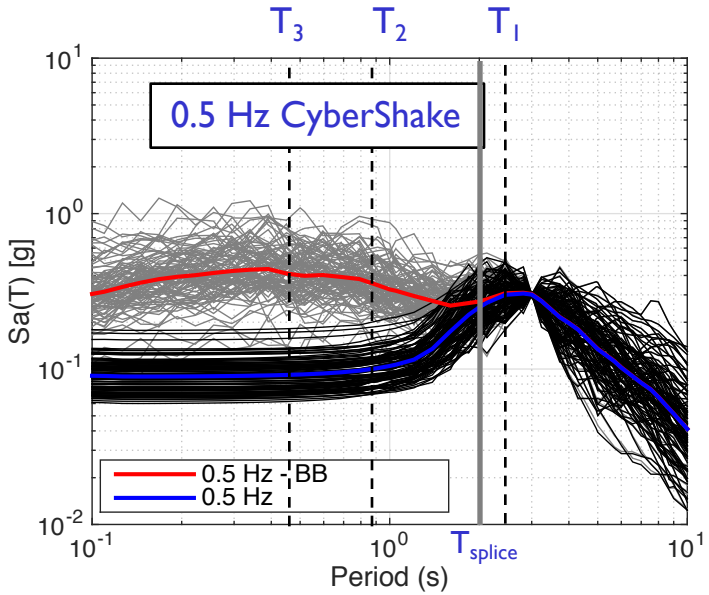


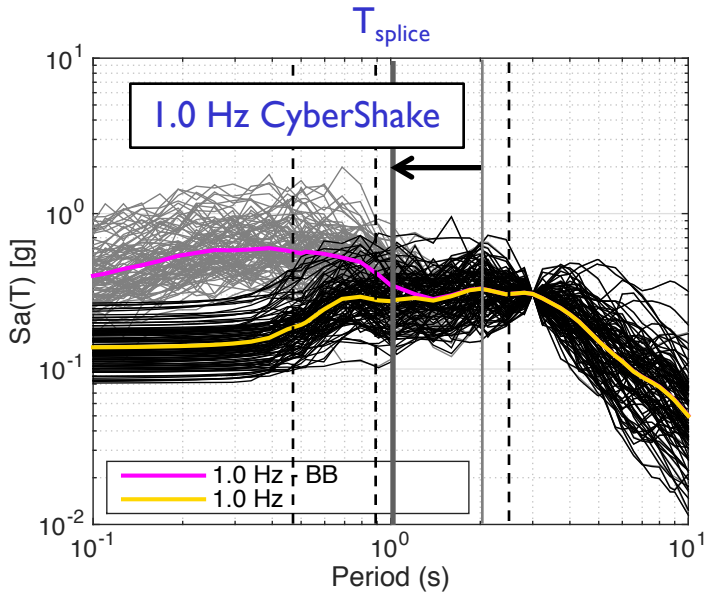
Story Drift Demands

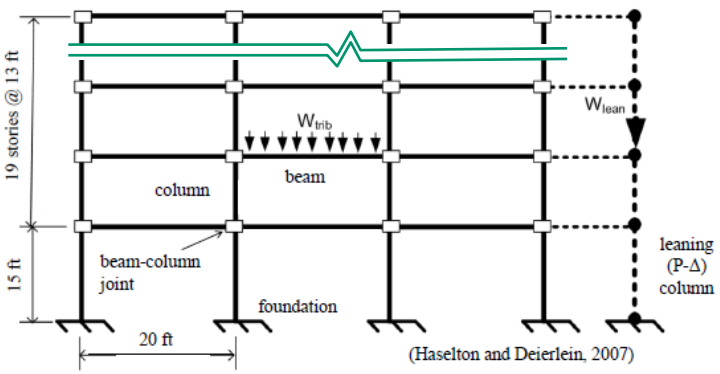


Sensitivity of Response to High Frequency in Ground Motions









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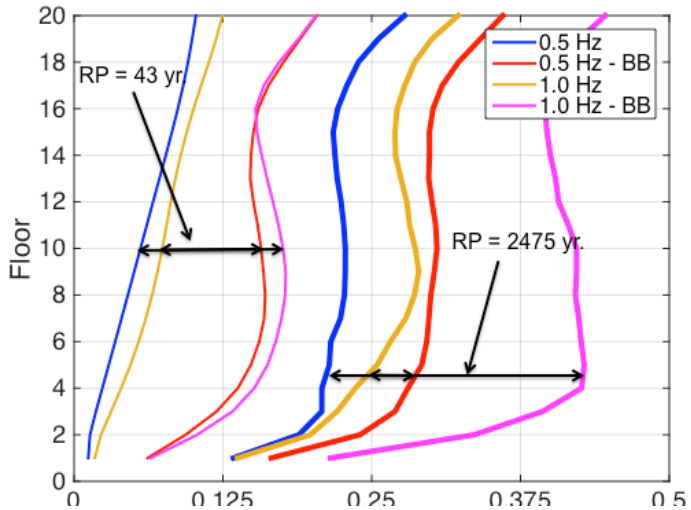
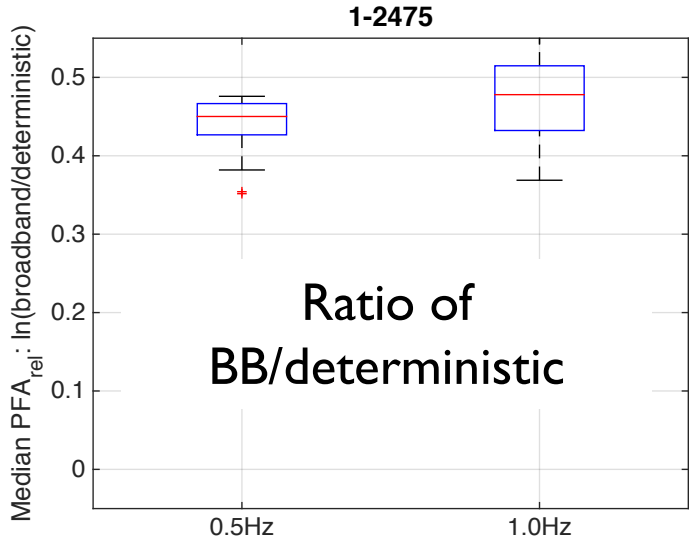


Peak Floor Accelerations



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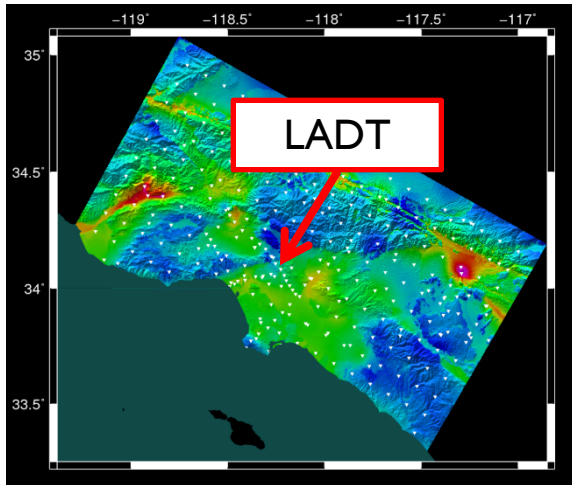

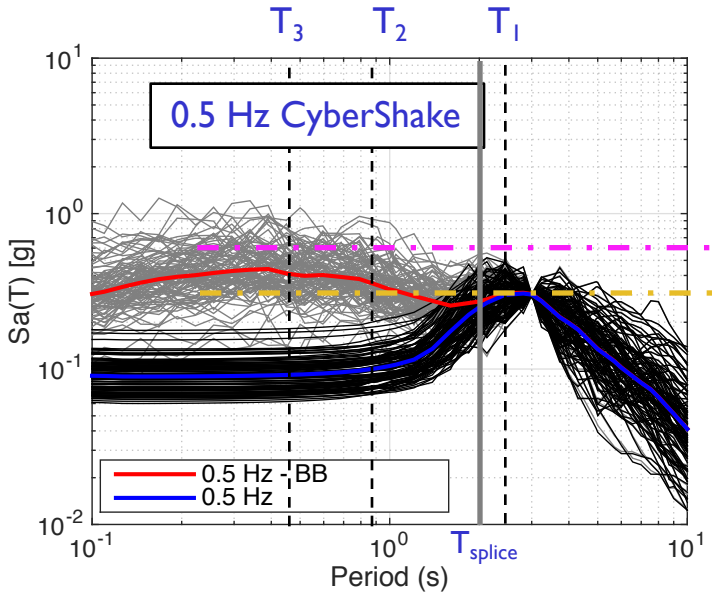

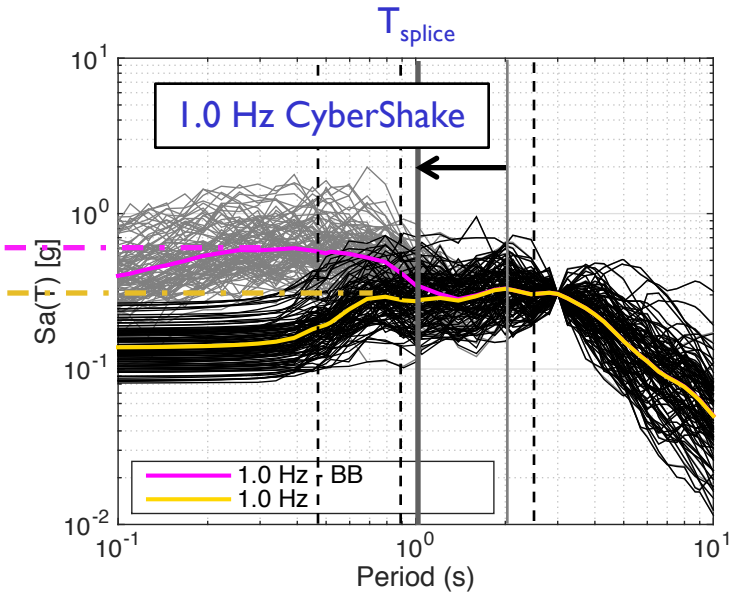

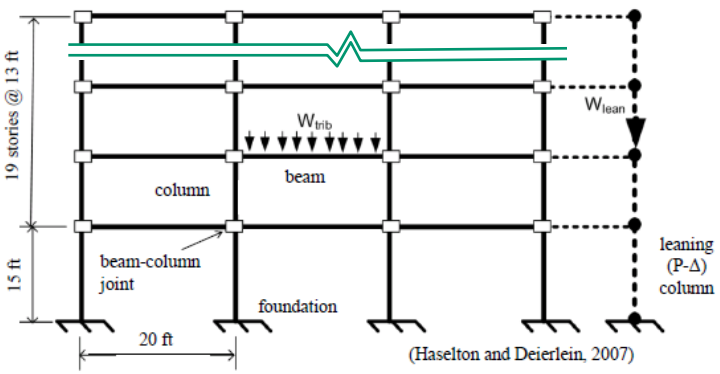

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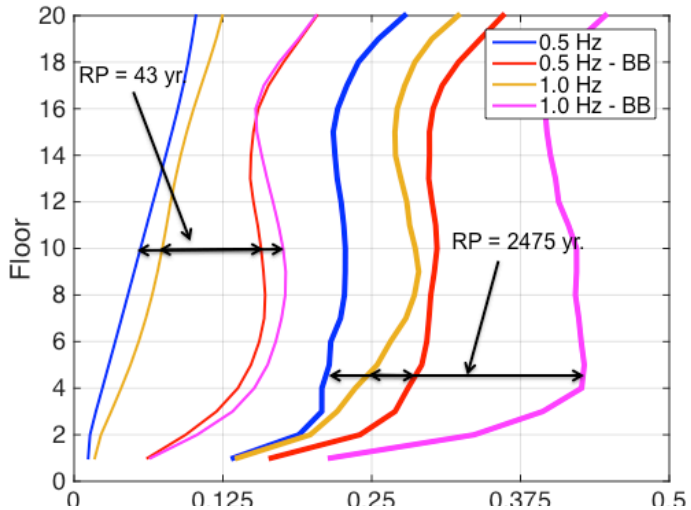

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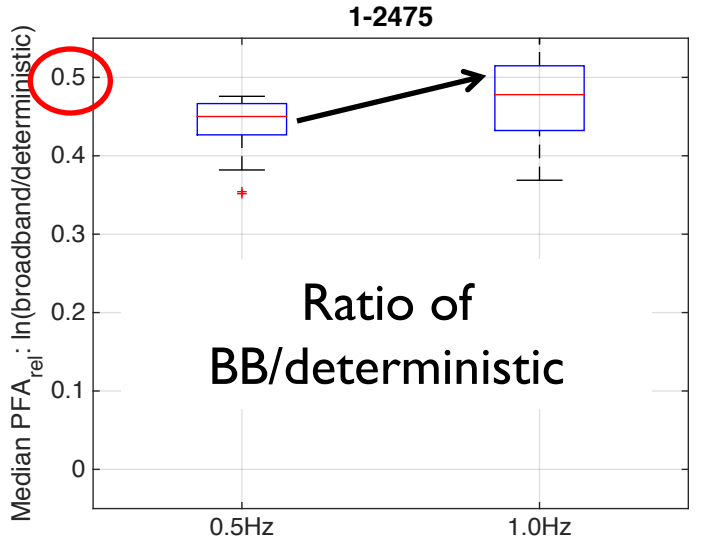
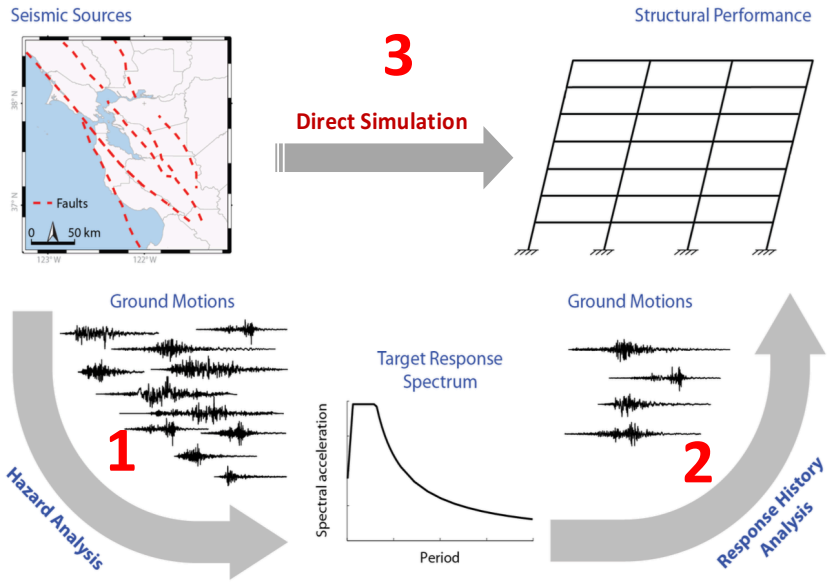


How can EQ simulations improve earthquake engineering



1) Improved Characterization of Seismic Hazard

- Reduced reliance on empirical GMPE's
- Refined Spectral Intensity Maps (coming up next!)
- Characterization of **other features** (duration, pulse effects, …)

2) Expanded Database of EQ Ground Motions

- Improved NL Dynamic Analysis (e.g., tall buildings)
- Reduced need for scaling of ground motions
- Reduced reliance on PSHA targets to select/scale motions

3) Direct Assessment using EQ Simulations

- Potentially, more straightforward
- Enabling research inquiries (e.g., risk deagg.; damaging features)
- Geographically distributed systems

Concluding Thoughts

- Simulations are most useful where they:
  - Provide **different answers** compared to conventional methods (PSHA w/recorded motions)
  - Address situations that are **outside the range** of conventional methods (large M; basin effects, directivity, etc.).

- To be really useful, simulations need to be reliable
  - Quantitative validation is important, but can only go so far
  - Role of risk deaggregation and sensitivity studies to highlight important contributors
  - More education and transparency to build confidence in models and assumptions

- More emphasis on the near-surface layer
  - Definition of interfaces: *earth – deep basin – upper soil layer*
  - Data model (distributed seismograms) to facilitate alternative models (plug/play)