Application and Validation of Simulated BBP & Cybershake Motions for Building Response Analyses

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Stanford | ENGINEERING
Civil & Environmental Engineering

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College of Engineering

Background

Broad objective: Test and validate the use of **simulated ground motions from SCEC's Broadband Platform (BBP) & Cybershake** in nonlinear response history analysis and collapse assessment of tall buildings.

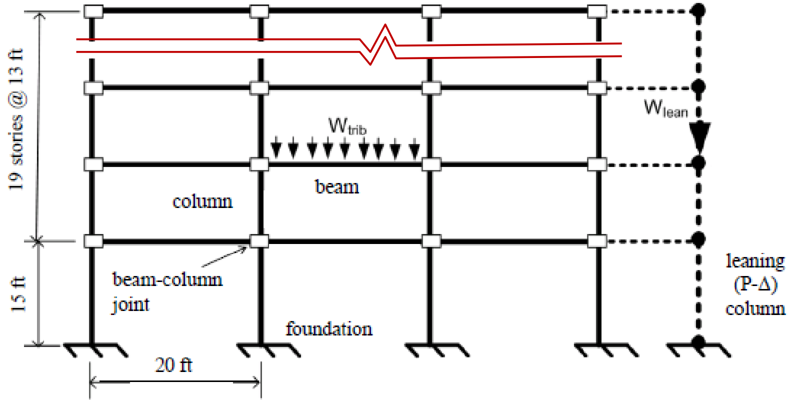
Scope*:* For two archetype buildings at three sites,

1. Select hazard-consistent ground motions for target hazard parameters (Sa response spectra intensity, shape and duration)
2. Analyzed structural responses under recorded and simulated motions, which are selected/scaled to the same target spectra
3. Contrast and evaluate building demand parameters
4. Identify the benefits and limitations of using simulated earthquake seismograms in engineering applications.

Archetype Buildings

20-story RC frame

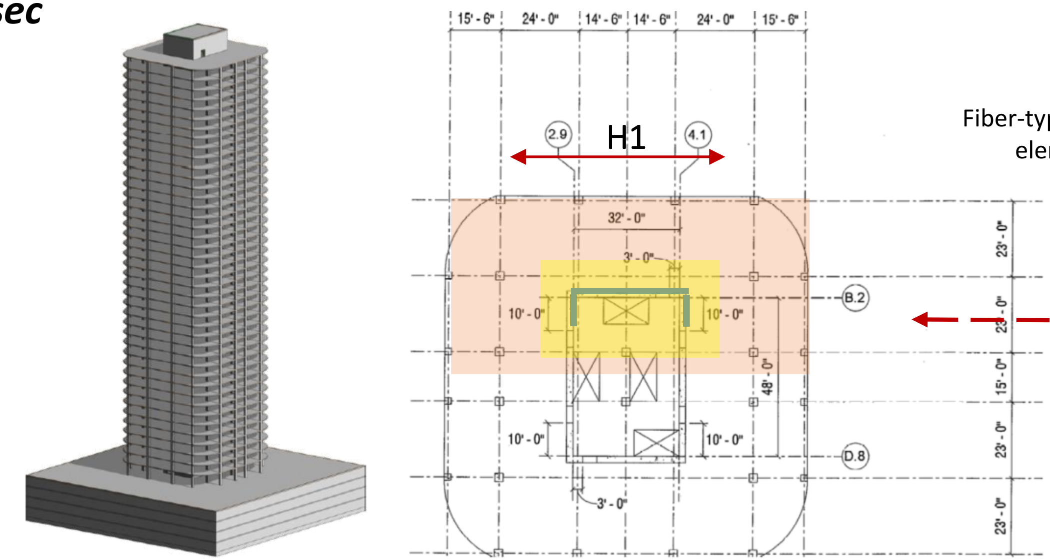
- ***Archetype ID:*** *1020 (FEMA P695)*
- ***Modeling:*** *Cyclic hinge model for beams and columns in the lateral frame + leaning system (gravity frame)*
- ***Period: T_1 = 2.6 sec, T2 = 0.9 sec***



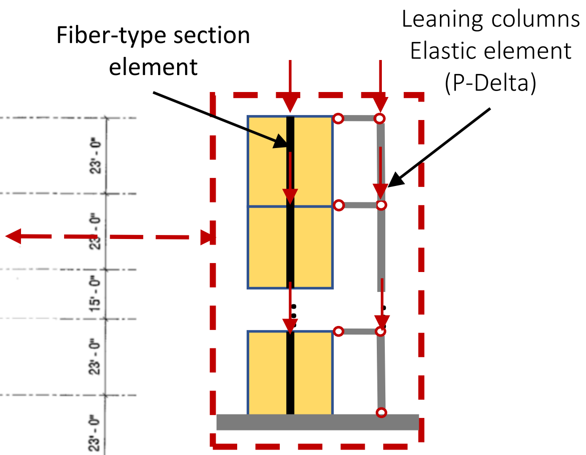
2D OpenSEES model: 20-story RC frame

42-story RC frame

- ***Archetype ID:*** *simplified from TBI building 1C (H1 direction)*
- ***Modeling:*** *force-based fiber element for shear wall + leaning system (gravity frame)*
- ***Period: T_1 = 4.2 sec, T_2 = 1.0 sec***



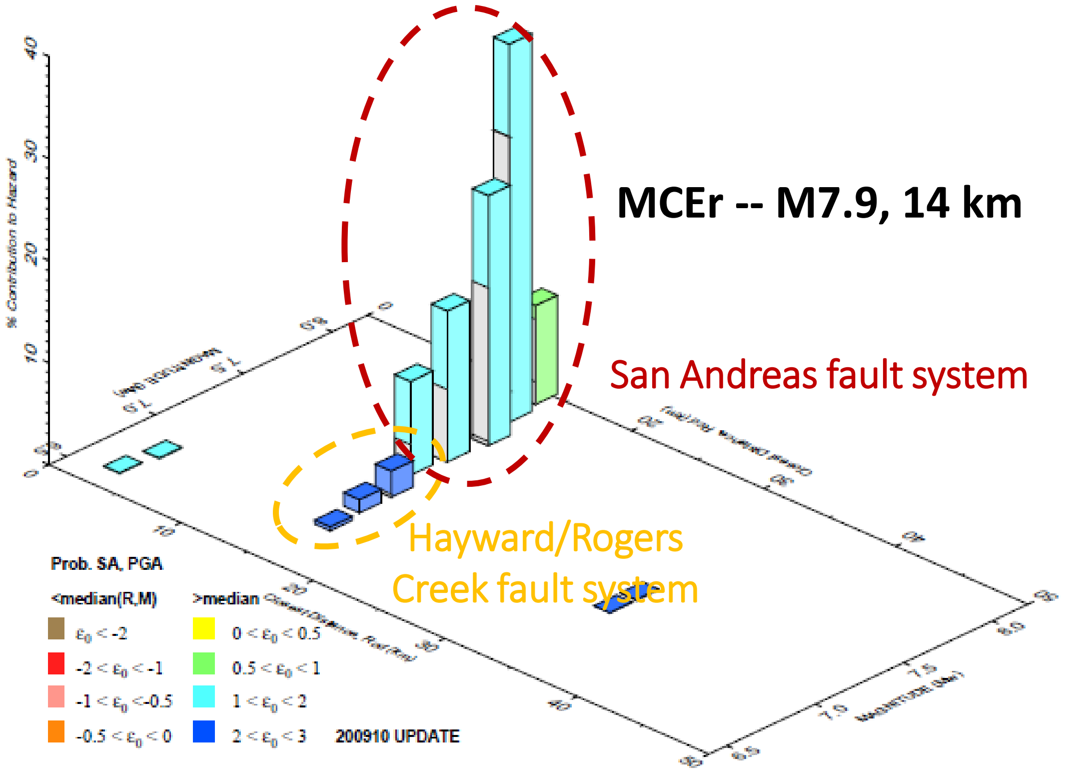
42-story shearwall building (PEER TBI)



2D OpenSEES model

Ref: PEER TBI (2011).

San Francisco Downtown, SFDT (8029-RIN)
[1728 BBP Records]



Major seismic sources for SFDT site

Key Focus Areas

GM selection

1. *Single-target IMs (Conditional Spectra + duration)*
2. *ASCE-7 MCEr procedure*
3. *Simulated BBP is more consistent with governing hazard (requiring less scaling)*

Structural response & collapse

1. *Ability to match targets*
2. *Sensitivity of response to GMs*
3. *Contrasting CS versus UHS*

Intensity Measures (IMs)

- **Target**: Conditional Spectra (***CS***)[1] and significant duration, $\boldsymbol{Ds_{5\text{-}75}}$[2]
- Prediction equations for spectral acceleration, Sa[3] and duration[4] with correlations to construct Generalized Conditional Intensity Measure (**GCIM**)[5]: *CS* + $Ds_{5\text{-}75}$

Ground motion selection

- Expanded selection algorithm[6] with different weights to CS and duration [7] to optimize selection
- **Results** (10%/50yr & 2%/50yr): Recorded **NGA** and simulated **BBP** motions **match target IMs well**

Ref:

[1]: Lin, Harmsen, Baker, & Luco (2013).

[2]: Chandramohan, Baker, & Deierlein (2016).

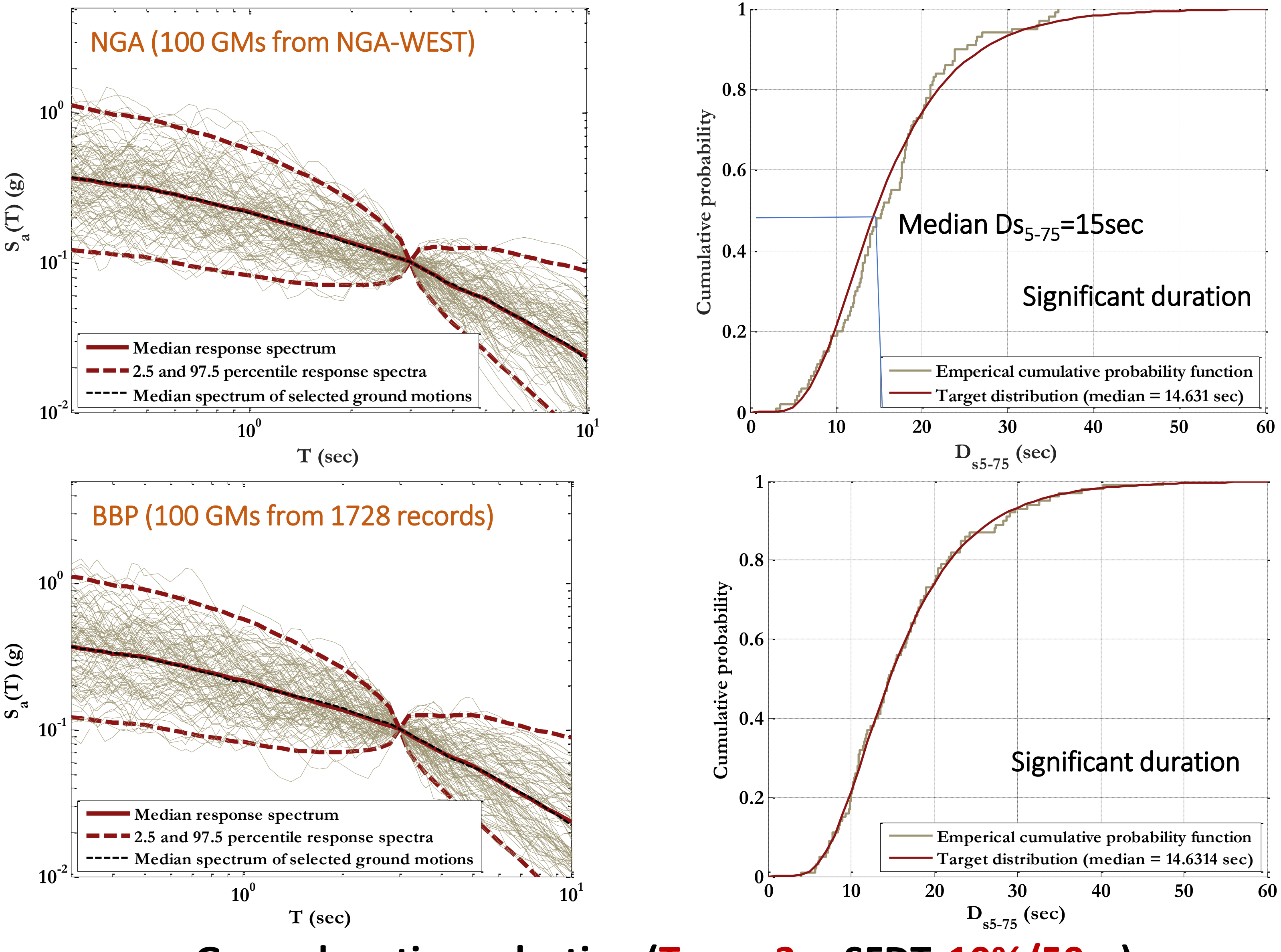
[3]: Campbell & Bozorgnia (2008).

[4]: Afshari & Stewart (2016).

[5]: Bradley (2010).

[6]: Jayaram, Lin, & Baker (2011).

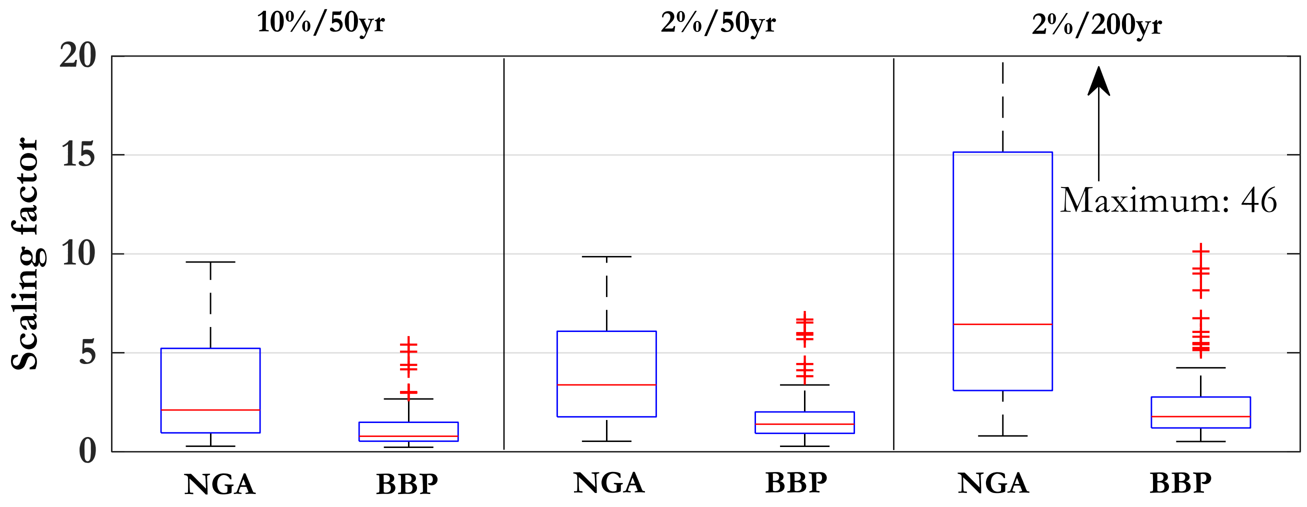
[7]: Bijelic, Lin, & Deierlein.



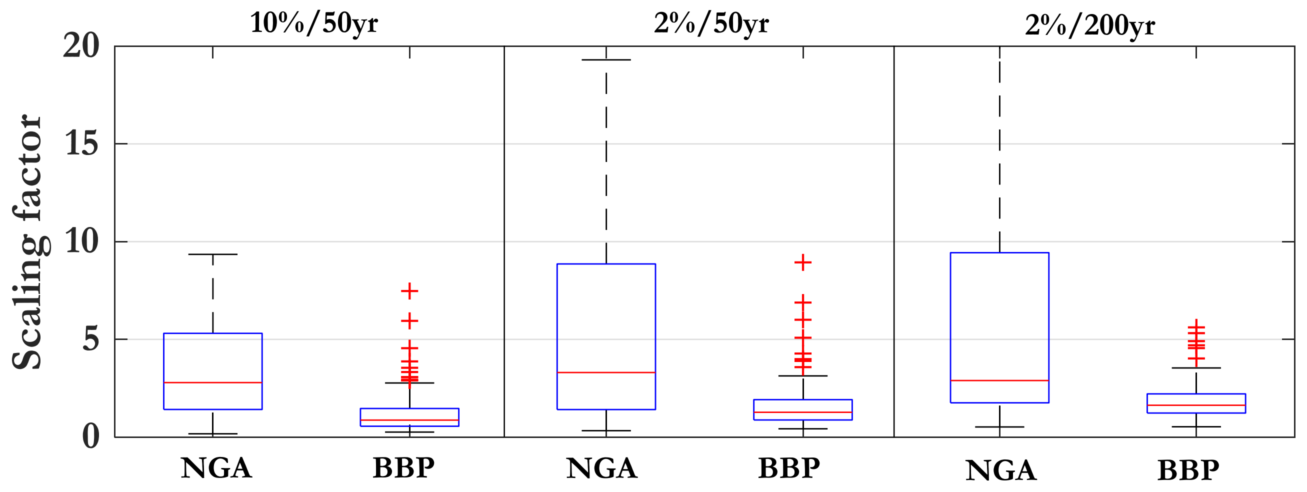
Ground motion selection (T_{cond} = 3 s, SFDT, 10%/50yr)

Scaling factor

- *Since **BBP** (v17.3, Part C) records are simulated from large events, they generally need much **smaller scaling factors** compared to NGA records*
- *The benefit of BBP (and simulations such as CyberShake) to avoid large scaling factors is apparent at high intensity levels*
- *Constrained by the number of simulation runs*



Scaling factors (SFDT, T_{cond} = 3 sec)



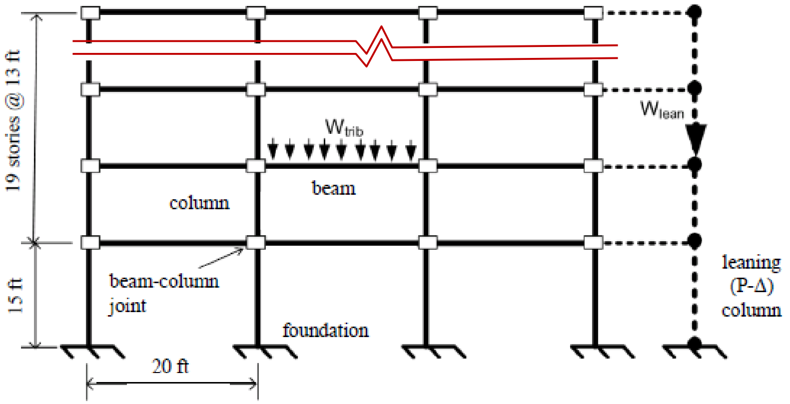
Scaling factors (SFDT, T_{cond} = 5 sec)

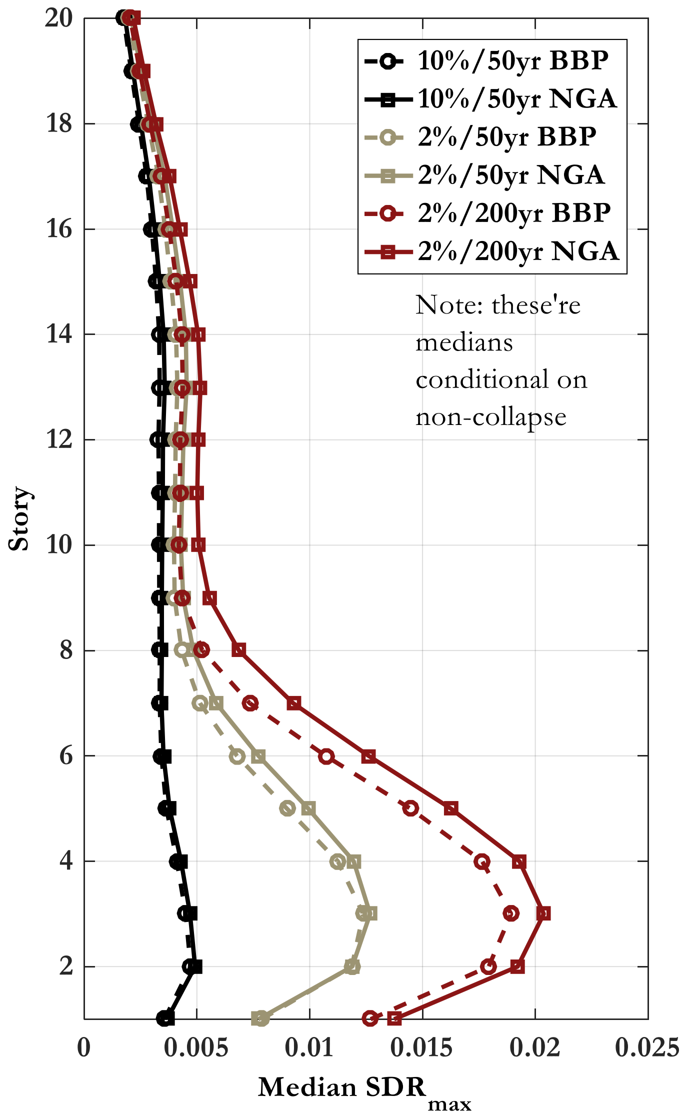
Multi-Stripe Analysis (MSA)

20-Story Frame Response

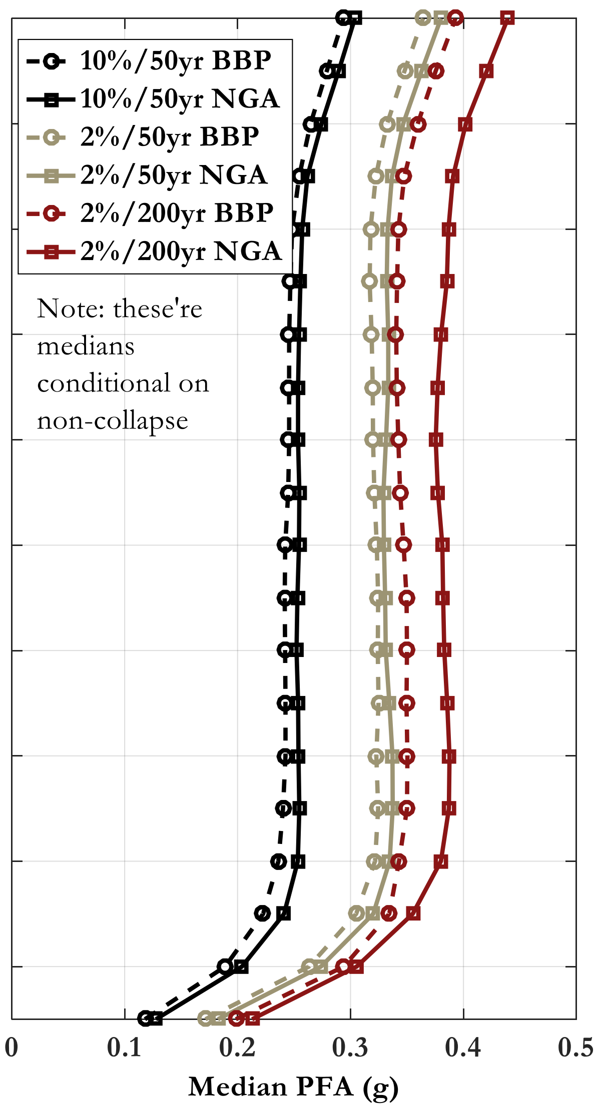
- *Maximum Story Drift Ratio (SDR_{max})*
  - *Comparable up to 2%/50yr*
  - *<10% difference under 2%/200yr*

- *Peak Floor Acceleration (PFA)*
  - *Comparable up to 2%/50yr*
  - *~10% difference under 2%/200yr*





Maximum Story Drift Ratio



Peak Floor Acceleration

Multi-Stripe Analysis (MSA)

20-Story Frame Response

- *Maximum Story Drift Ratio (SDR_{max})*
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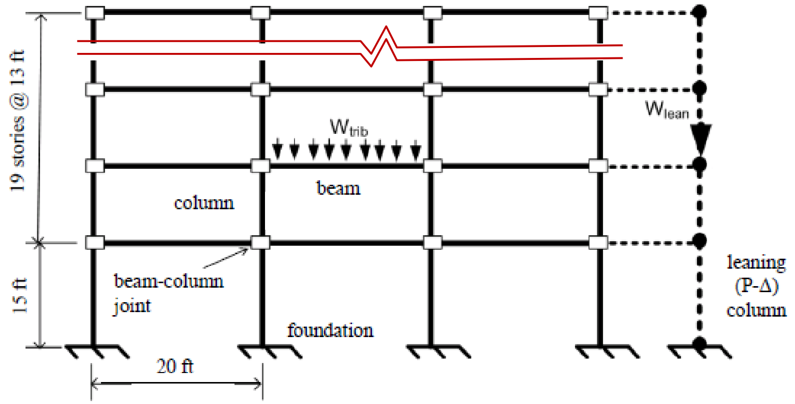
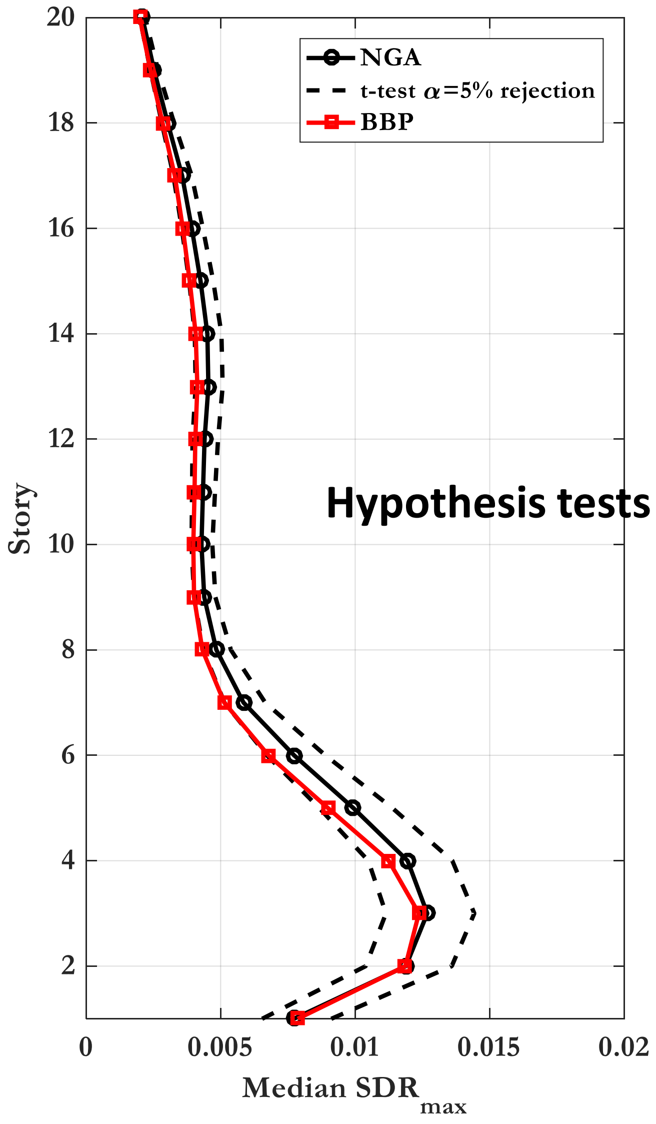
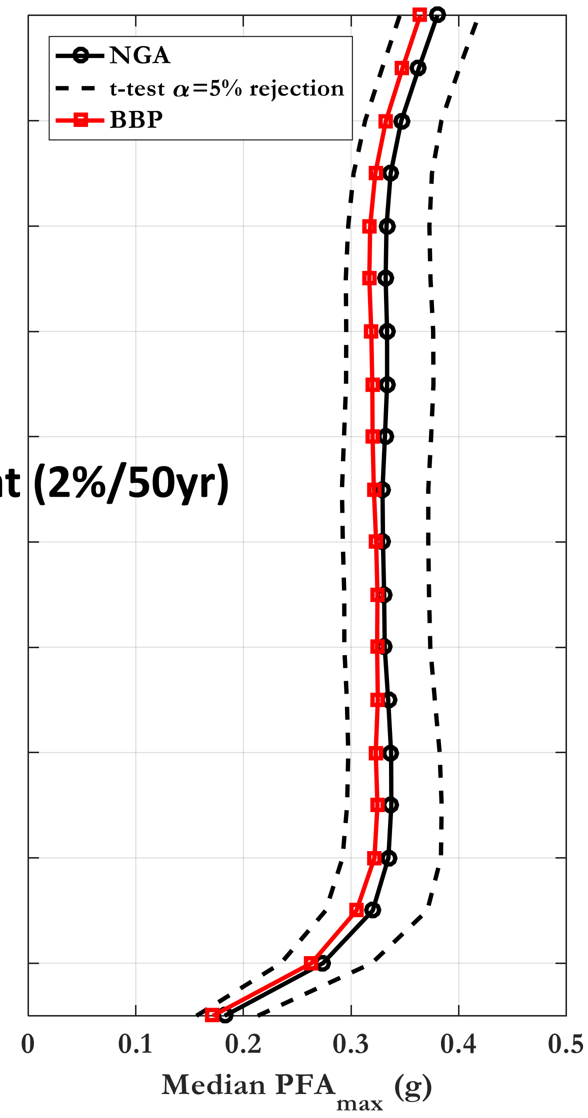




Hypothesis tests at (2%/50yr)

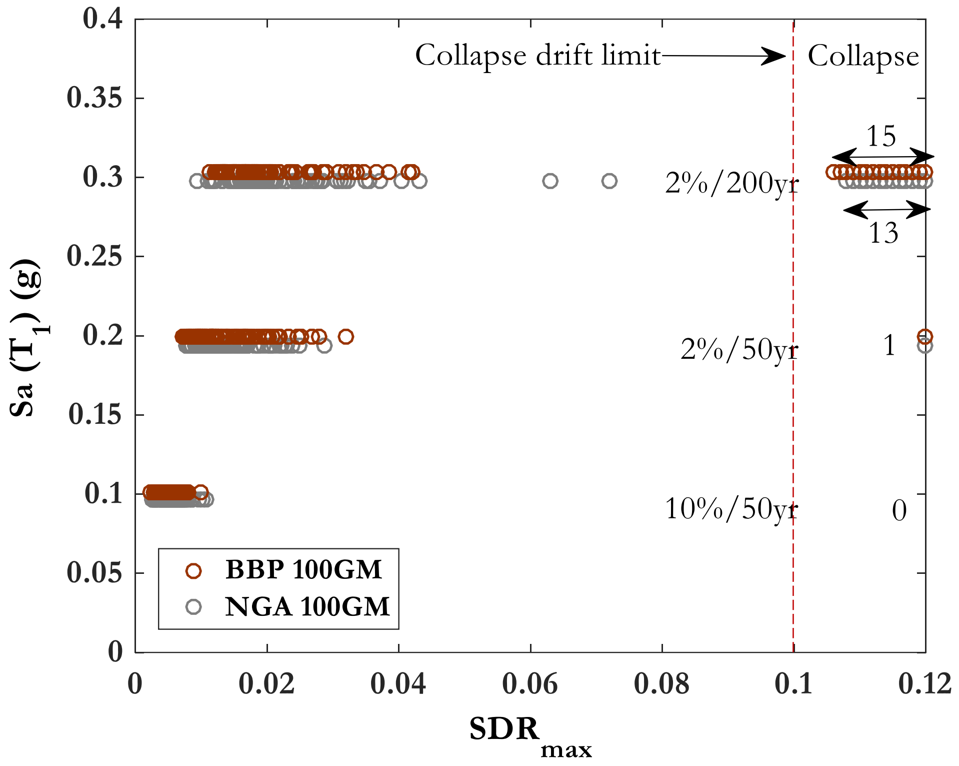


Maximum Story Drift Ratio

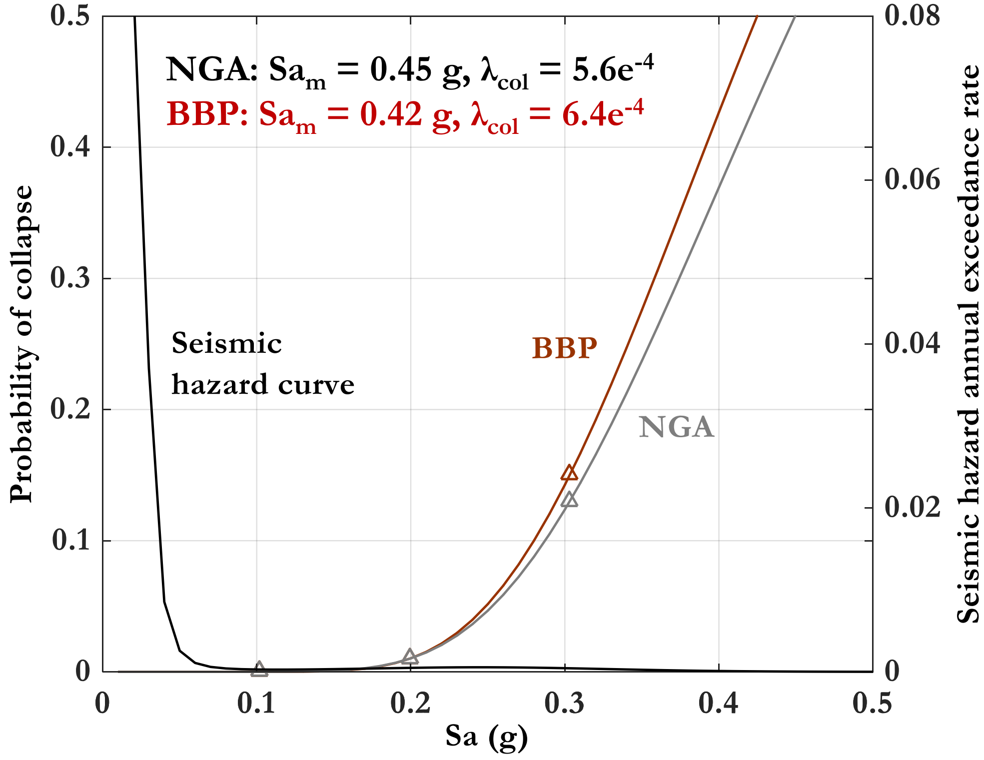
Peak Floor Acceleration

Collapse risk (20-story RC frame)

- *NGA and BBP motions yield the same number of collapses at 10%/50yr and 2%/50yr levels*
- *Collapse (2%/200yr): BBP 15 vs. 13 NGA*
- *About 7% difference in median collapse intensity and about 15% difference in mean annual frequency (MAF) of collapse*



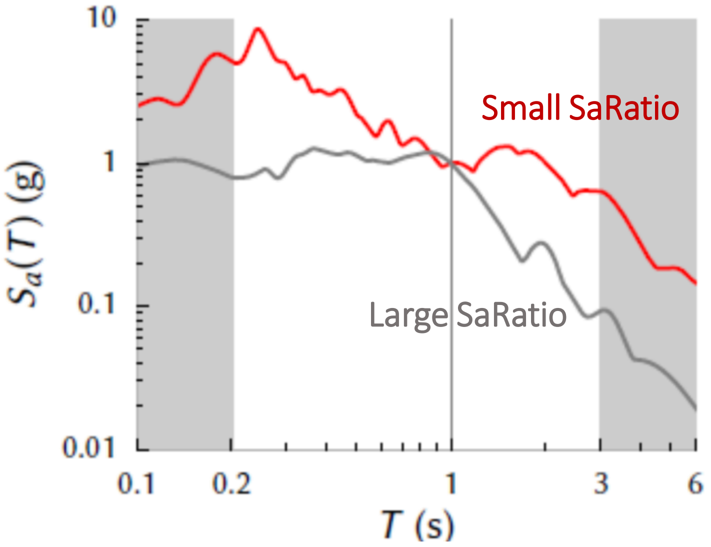
Stripe Analysis - Story Drift Ratios



Collapse Fragilities

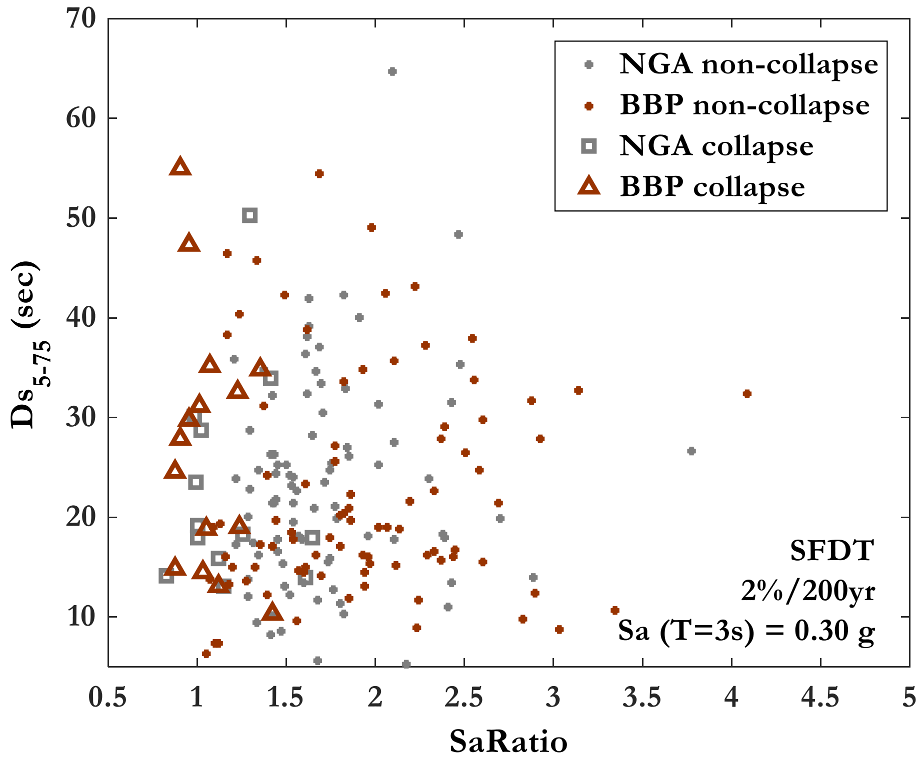
Collapse deaggregation (20-story RC frame)

Although both selected GM sets fit the target Conditional Spectra, the BBP set has more records with smaller SaRatio's. This contributes to a slightly higher estimated collapse probability at 2%/200yr.



$$Sa,avg(T_0,T_2) = \exp\left[\frac{\int_{T_0}^{T_2} \ln Sa(\tau)\,d\tau}{T_2 - T_0}\right]$$

$$SaRatio(T_0,T_1,T_2) = \frac{Sa(T_1)}{Sa,avg(T_0,T_2)}$$



Collapse deaggregation (100 GMs)

Sa,average & SaRatio

- *Sa,avg: average PSA values over a period range*
- *SaRatio: the ratio between Sa(T_1) and Sa,avg, which describes the period-dependent spectral shape*

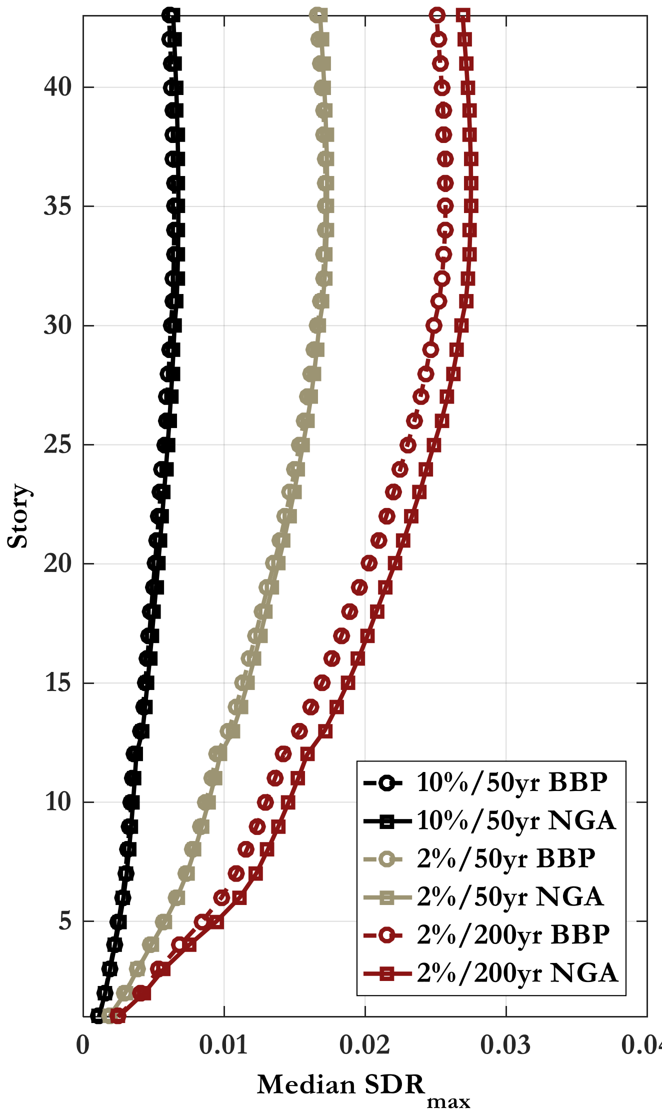
Ref: Eads, Miranda, & Lignos (2016).

Multi-Stripe Analysis (MSA)

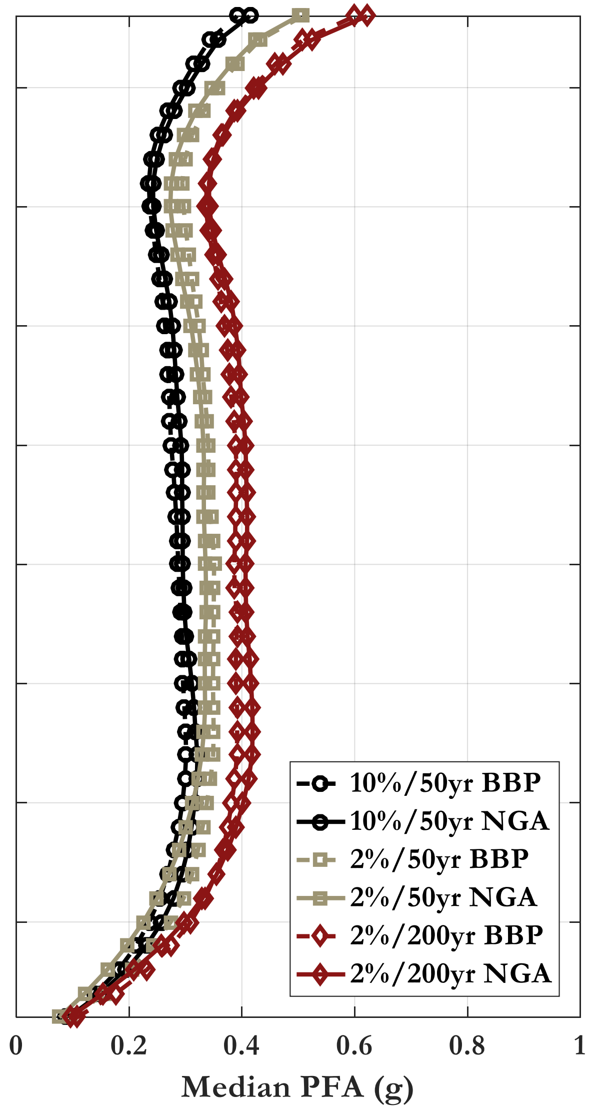
42-story shearwall

- *Maximum Story Drift Ratio (SDR_{max})*
  Comparable up to 2%/50yr
  <10% difference under 2%/200yr

- *Peak Floor Acceleration (PFA)*
  Comparable up to 2%/50yr
  <10% difference under 2%/200yr



Maximum Story Drift Ratio

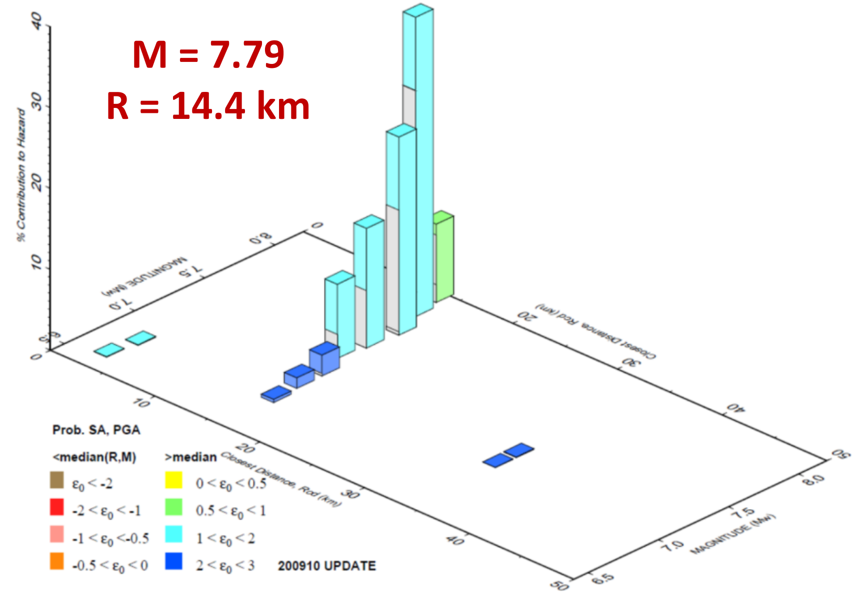


Peak Floor Acceleration

ASCE 7-16 Procedure

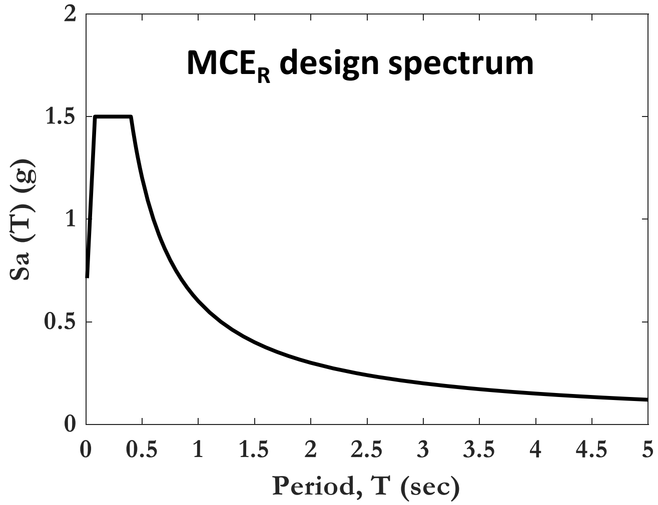
Ground motion selection

- *Site information:*
  - *Site class: B*
  - *Ss = 1.5 g*
  - *S1 = 0.6 g*
- *Target: ASCE 7-16 MCE_R/DBE spectrum*
- *Record number: 11*
- *Criteria:*
  - *Consistent M, R, and mechanism*
  - *Close site condition*
  - *Mean Sa >= target over ($0.2T_1$ ~ $1.5\ T_1$)*



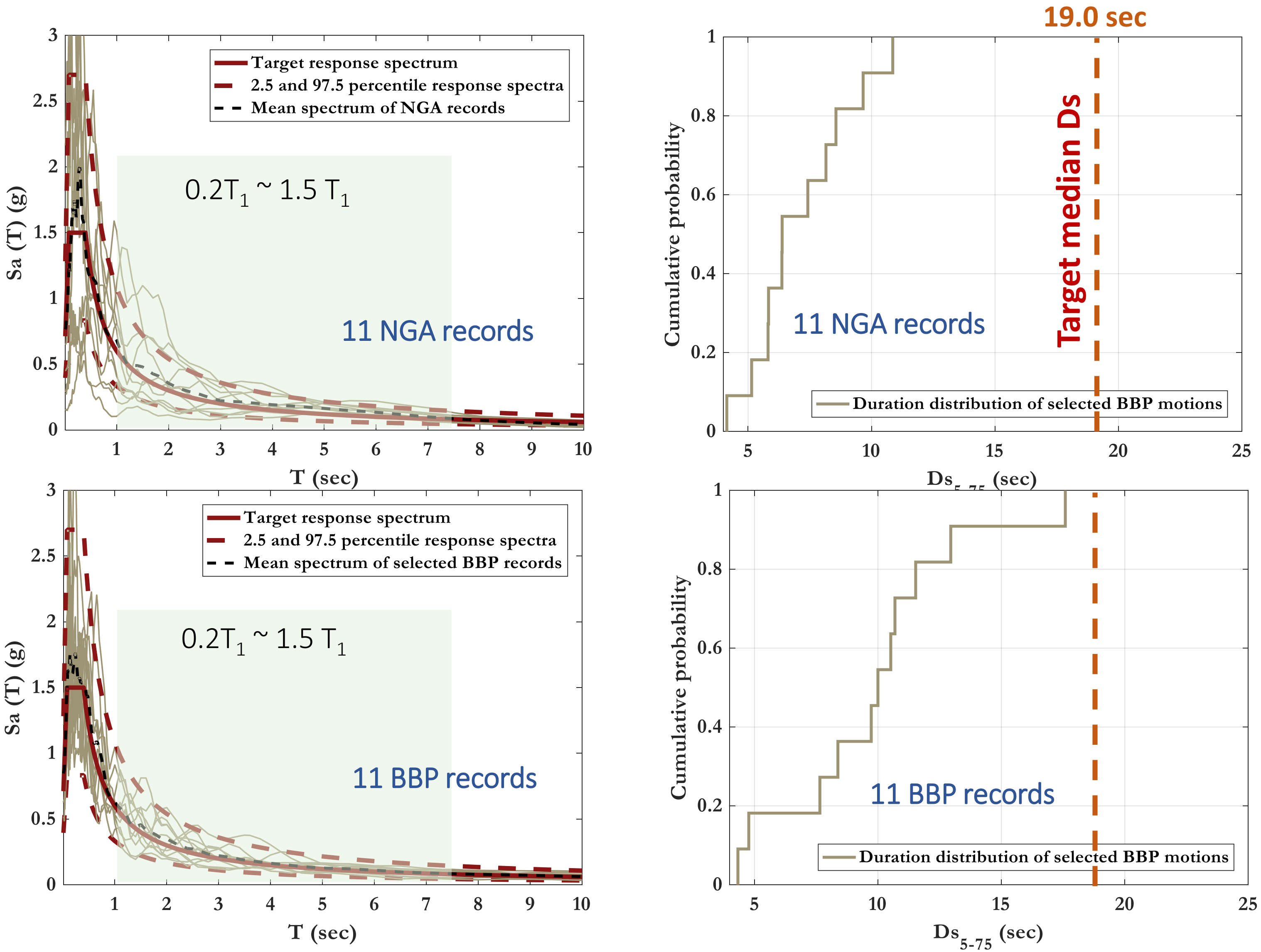
Seismic hazard deaggregation at 2% in 50 years intensity for 8029-RIN (after USGS)

MCE$_R$ and design response spectrum from ASCE-7 (after USGS design tool)

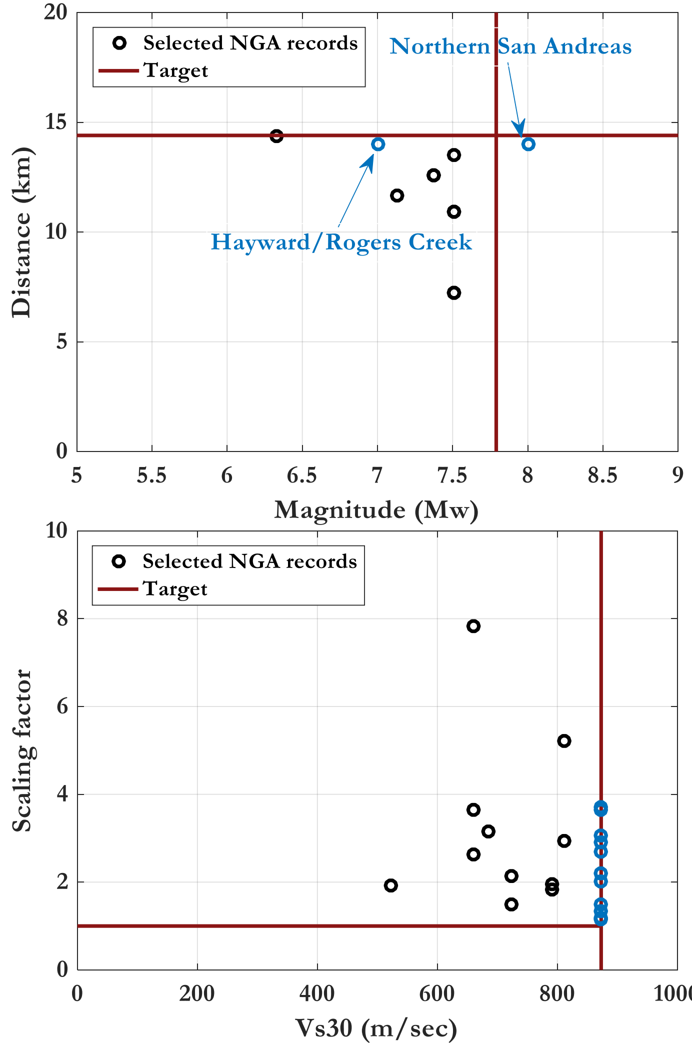


Ref: USGS webtool, https://earthquake.usgs.gov/designmaps/us/application.php

MCEr, T = 5 sec: selected NGA vs. BBP records



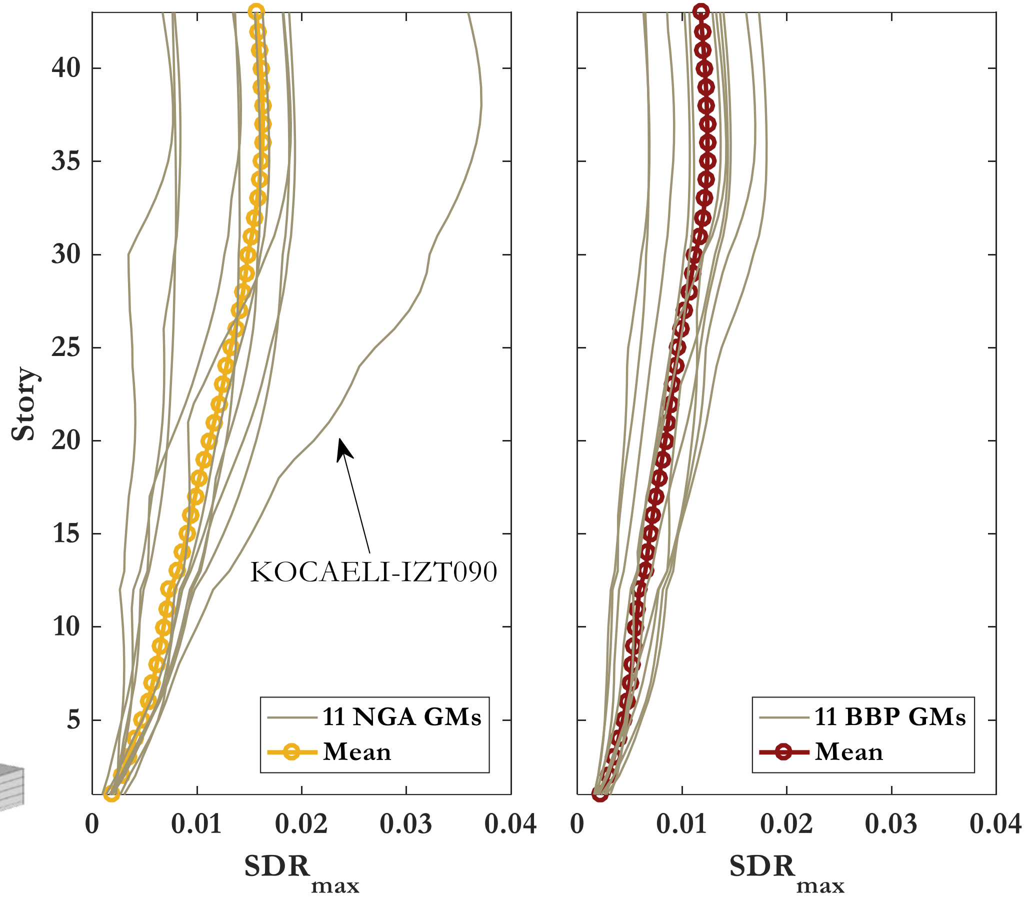
Comparison between selected 11 NGA and BBP records (Sa and duration)



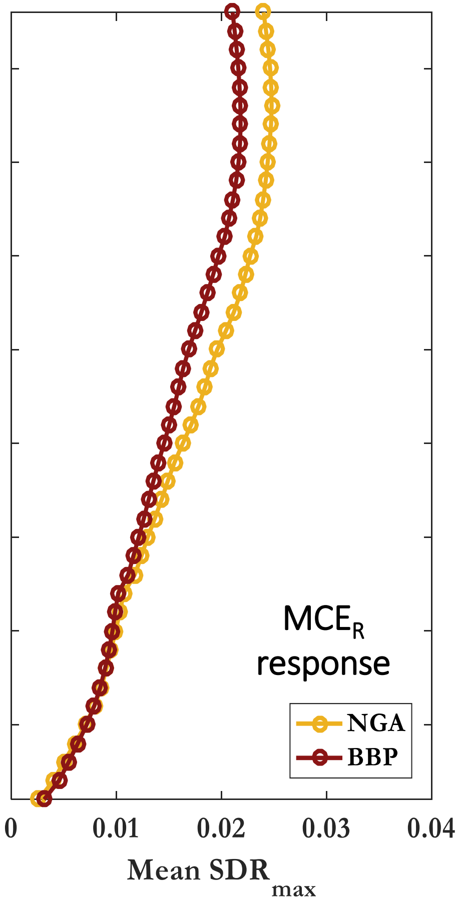
Causal comparison (M, R, Vs30, and scaling)

42-Story Shear Wall Response

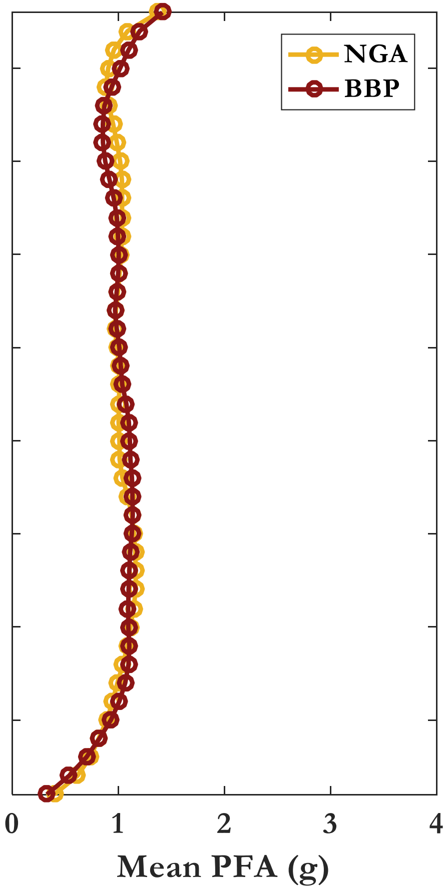
- *Effects from longer duration is insignificant (drift is modest)*
- *NGA: drifts ~10% larger*
- *BBP: smaller variation in response*



Story Drift Ratio (DBE)



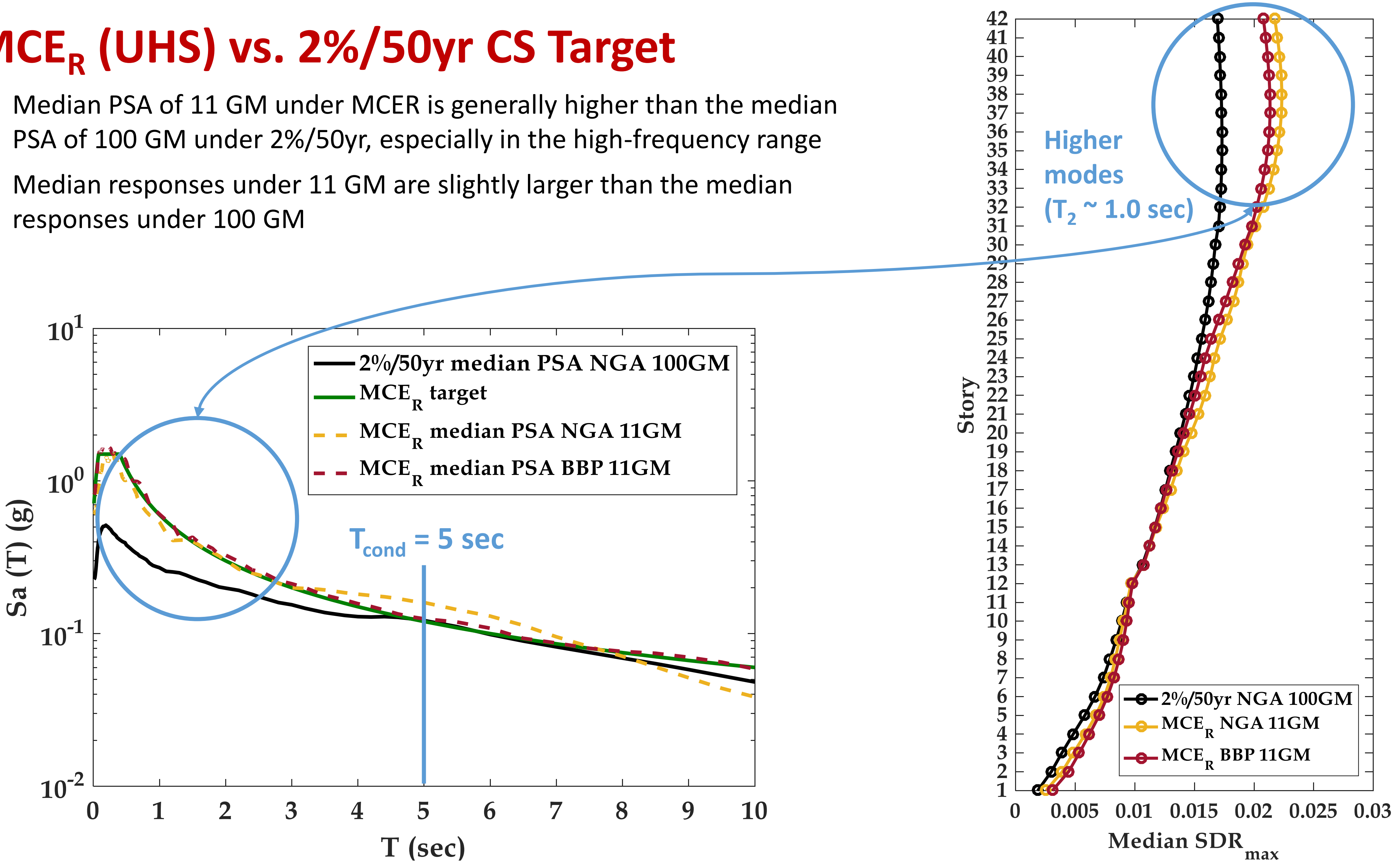
Story Drift (MCEr)



Accel. (MCEr)

MCE_R (UHS) vs. 2%/50yr CS Target

- Median PSA of 11 GM under MCER is generally higher than the median PSA of 100 GM under 2%/50yr, especially in the high-frequency range
- Median responses under 11 GM are slightly larger than the median responses under 100 GM



Summary (San Francisco Site)

1. Simulated (BBP) motions can be selected/scaled to match the PSHA target IMs (CS+$D_{s5\text{-}75}$) with *much smaller scaling than existing recorded motions.*

2. When ground motions are selected/scaled to comparable target IMs, there are no statistically significant differences in *calculated structural responses and collapse risks between recorded and simulated motions.*

3. Strictly following ASCE-7 guidelines (matching magnitude, mechanism and soil conditions), BBP simulations:

   a) provide a better fit to the response spectra target (e.g., MCE_R) with *less dispersion and closer match to expected durations,*

   b) can *avoid "unrealistic" spectral shapes* in selected records, thus offering more reliable response prediction from a limited number of ground motions.

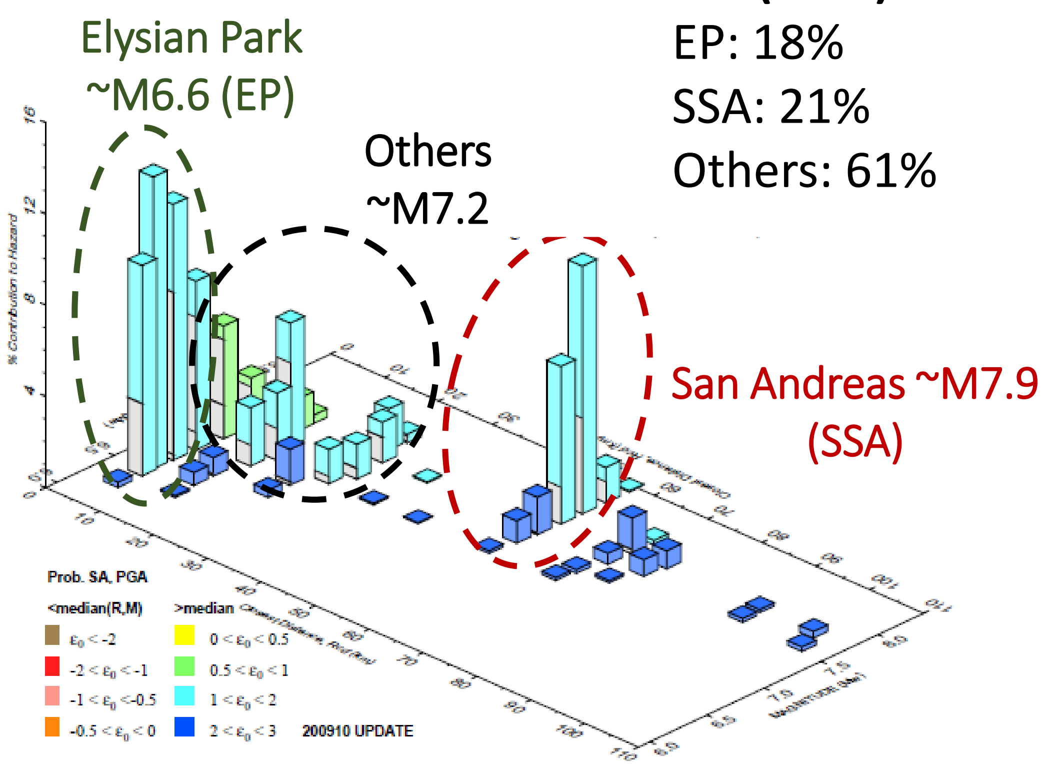
Los Angeles Downtown (LADT)

MCEr (T=5s):

EP: 18%

SSA: 21%

Others: 61%



Major seismic sources for LADT site

Key Focus Areas

GM selection

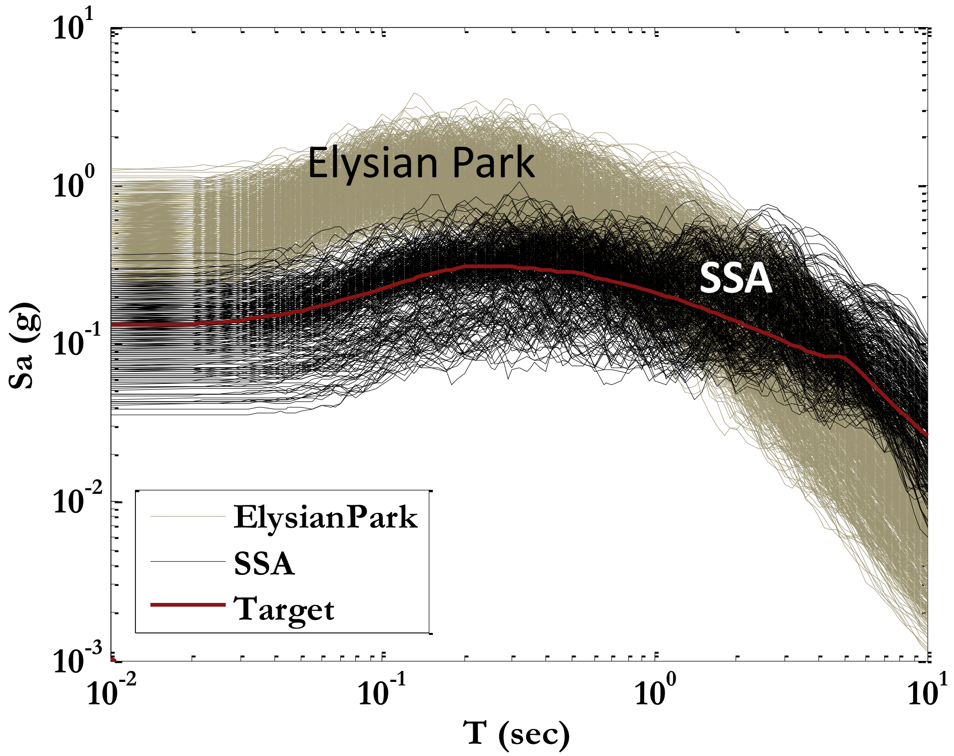
1. *Multi-target IM's*
2. *Spectral shape of Elysian Park records*

Structural response & collapse

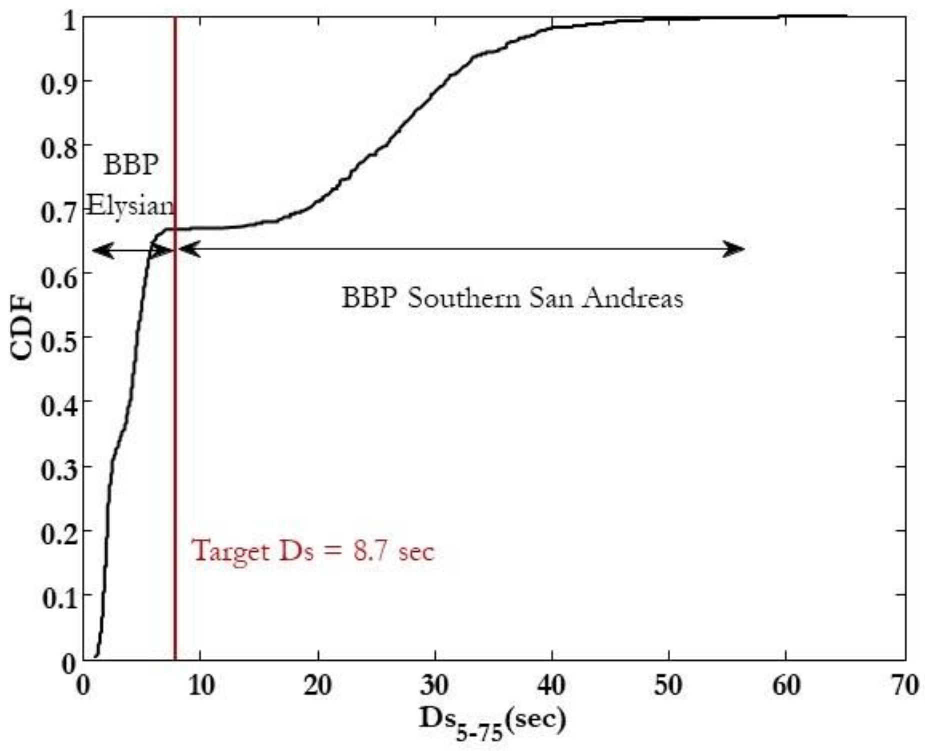
1. *Investigate sensitivity to different GMPE*
2. *Investigate sensitivity to records with different causal parameters*

Multi-target selection (LADT)

1. *Competing seismic sources: (1) South San Andreas, (2) Elysian Park, and (3) others (e.g., Puente Hills) whose **mechanisms and GM characteristics are very different***
2. *Select ground motions **for each major source target** based on their relative contributions to the total hazard (dependent on T_1 and return period)*



Target Spectrum vs. EP & SSA simulations
(LADT, 10%/50yr, T_{cond} = 5 sec)

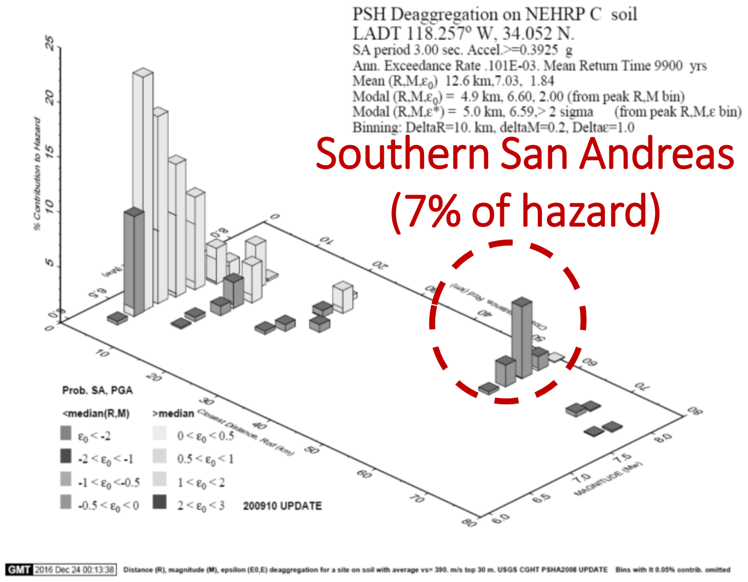


Target Duration vs. EP & SSA simulations
(LADT, 10%/50yr, T_{cond} = 5 sec)

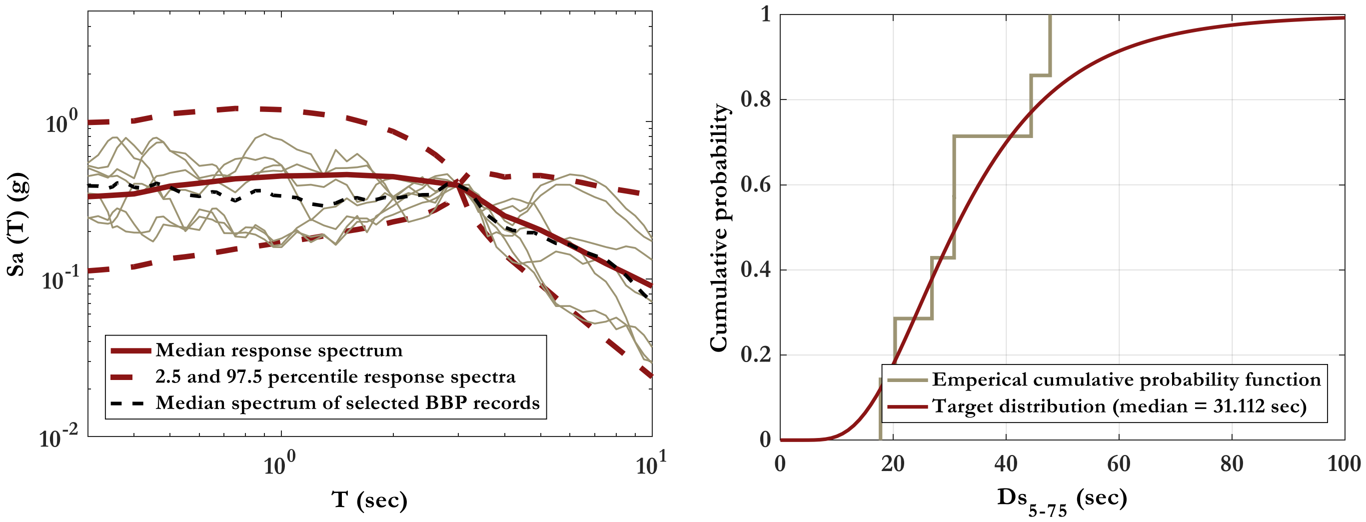
Ref: Lin, Harmsen, Baker, & Luco (2013).

Southern San Andreas (T=3s, 2%/200yr)

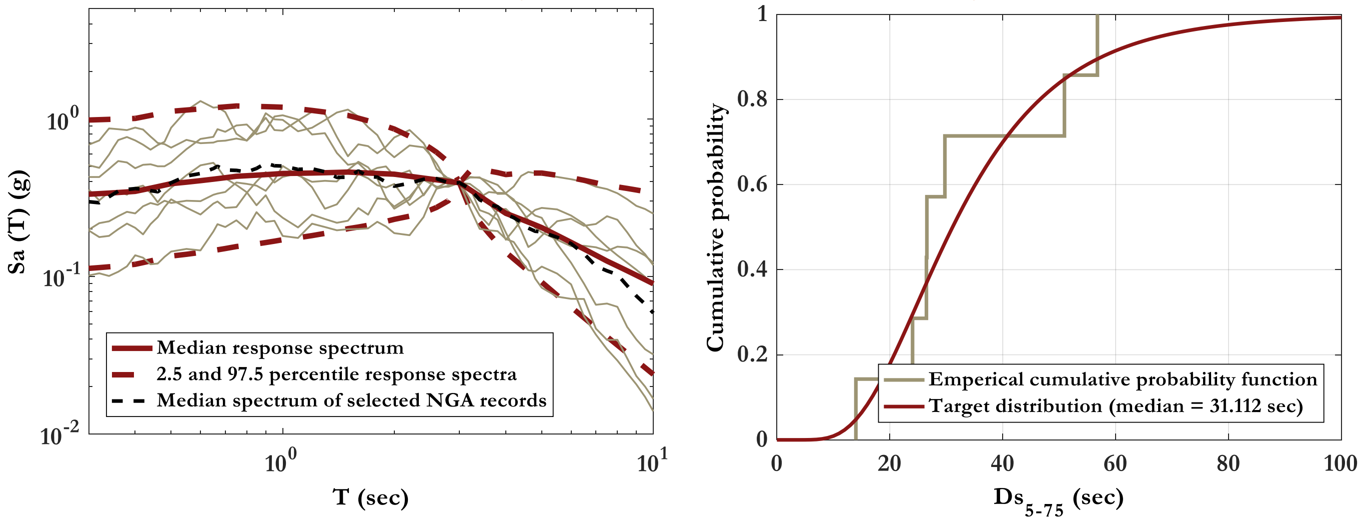
Reasonable match to the targets for both BBP and NGA motions at all 3 intensities.



BBP (7 GMs from 352 Southern San Andreas)



NGA (7 GMs from NGA-WEST)

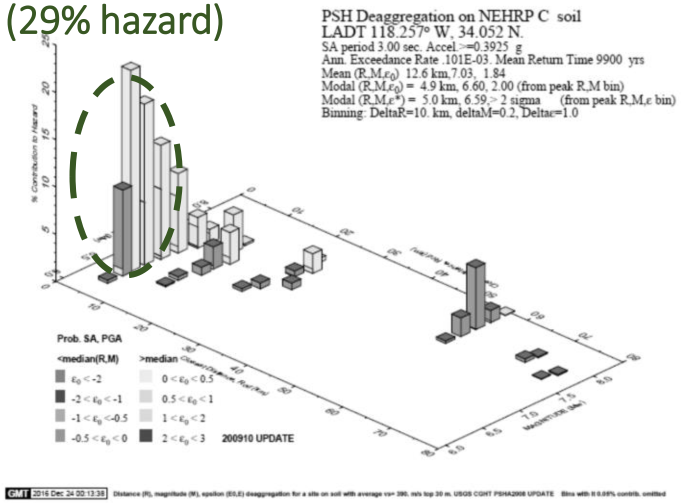


Ground motion selection (T_{cond} = 3 s, LADT, 2% in 200 years)

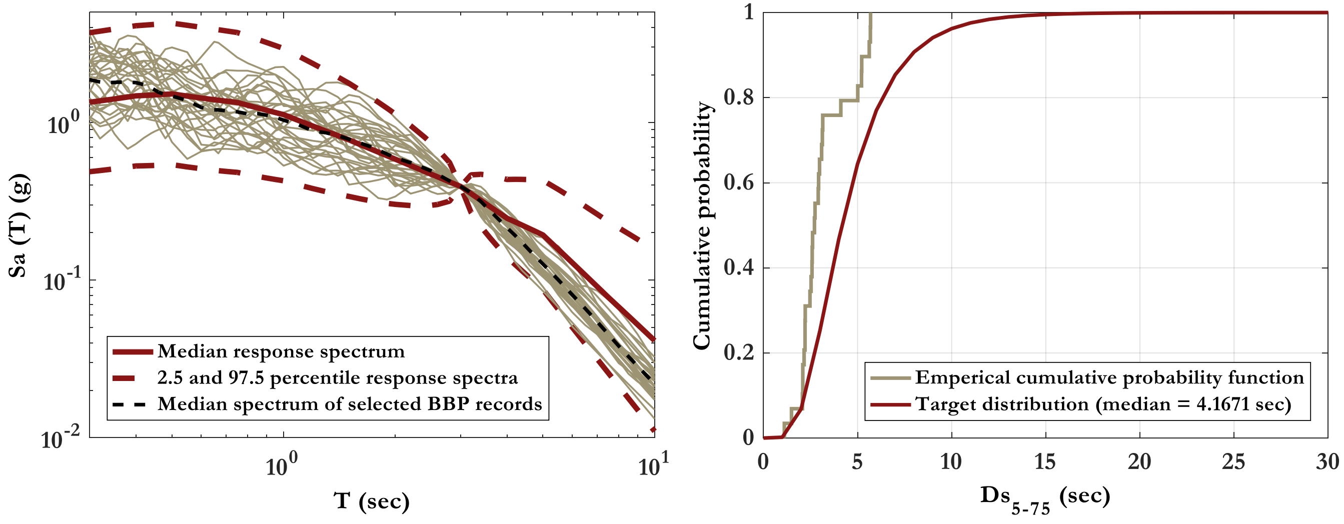
Elysian Park
(T=3s, 2%/200yr)

- *Good agreement between selected records and target up to 2%/50yr level*
- ***Discrepancy in BBP motions for 2%/200yr hazard***

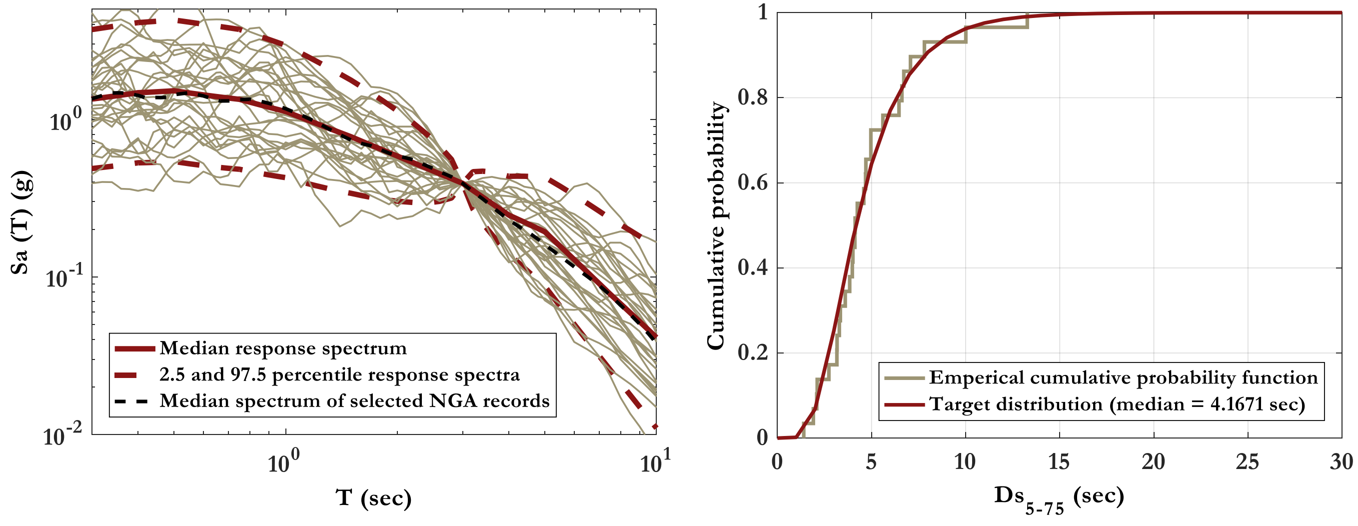
Elysian Park
(29% hazard)



BBP (29 GMs from 704 Elysian Park)



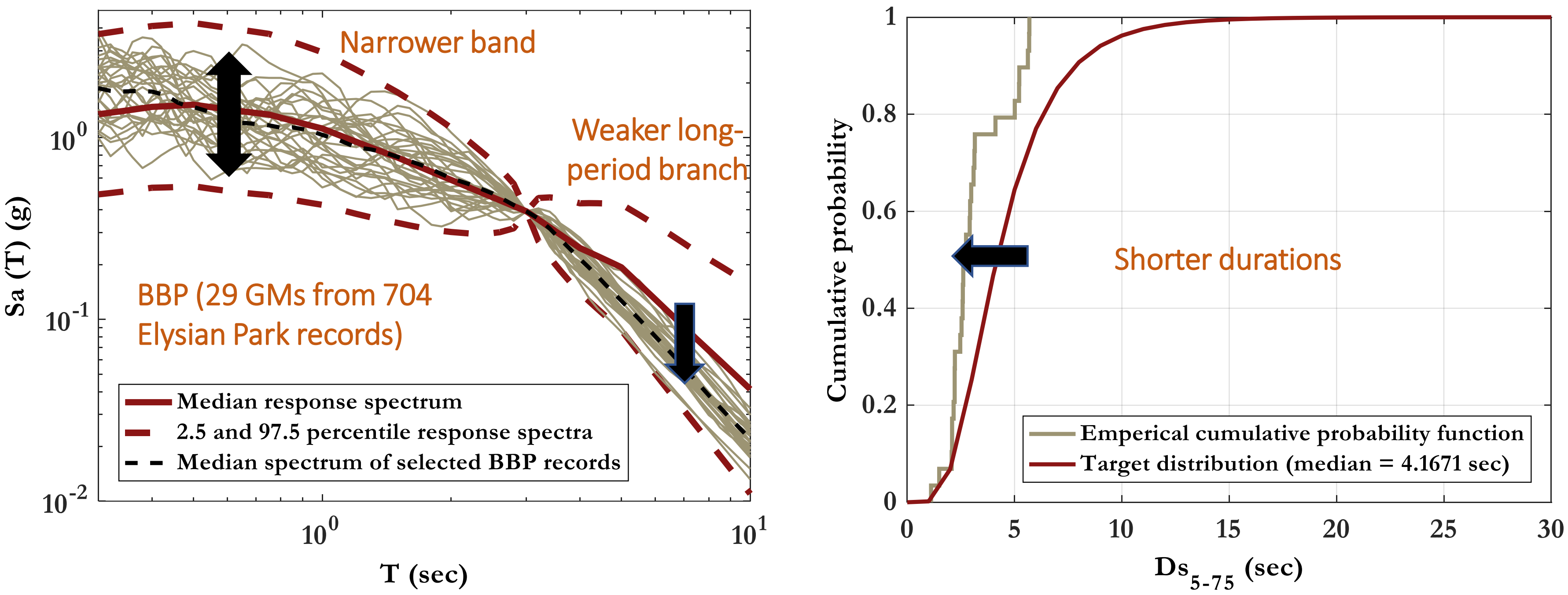
NGA (29 GMs from NGA-WEST)



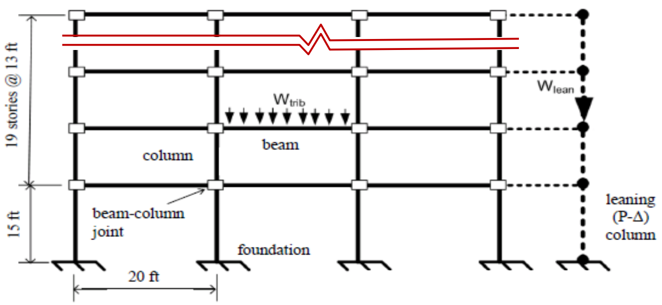
Ground motion selection (T_{cond} = 3 s, LADT, 2% in 200 years)

Discrepancies in selected BBP Elysian Park records at 2% in 200 yr hazard

1. ***steeper descent*** *in the long period range*
2. ***less variability*** *in the short period range*
3. ***shorter durations***

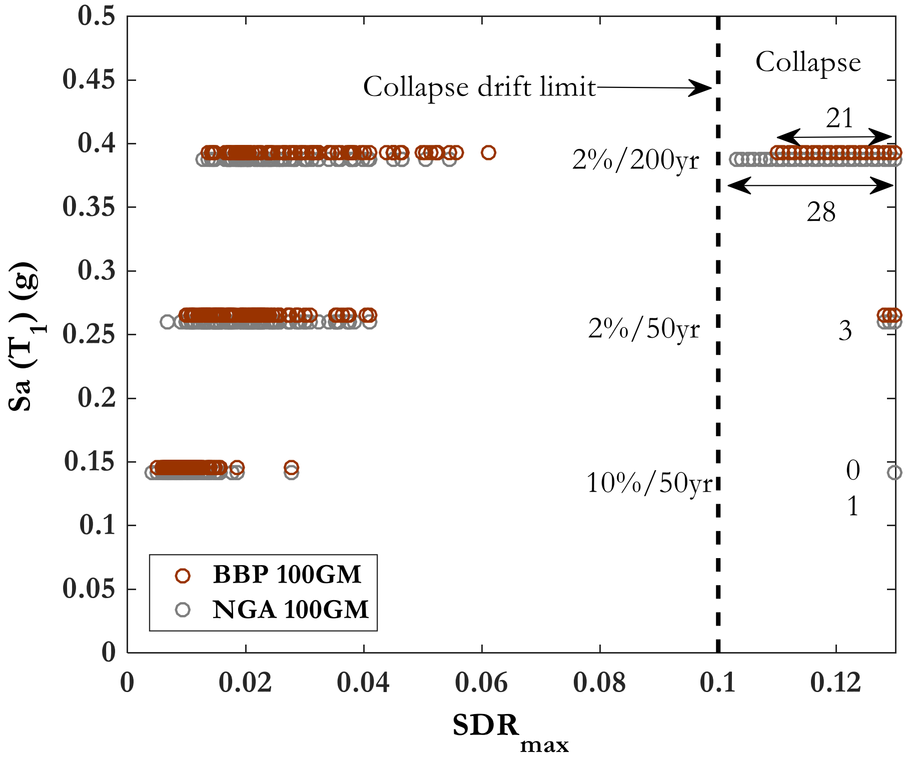


Target vs. Sa and duration distribution of selected BBP Elysian Park records
(LADT, 2% in 200yr, T_{cond} = 3 sec)

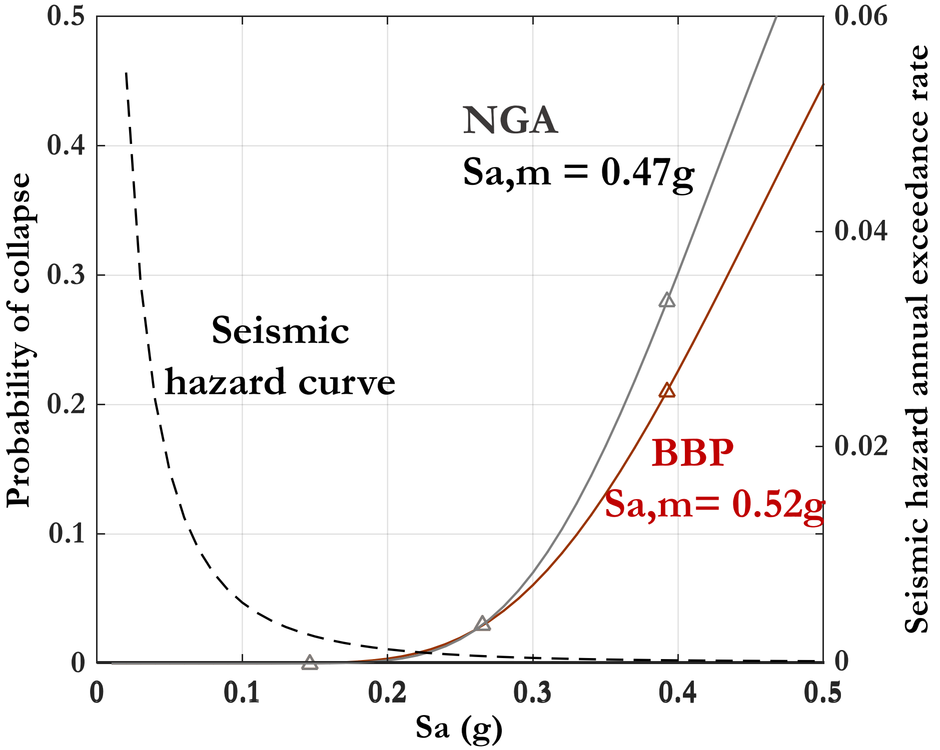


Collapse risk: 20-story frame (LA Downtown)

- *NGA and BBP motions yield same number of collapses up to 2% in 50 years hazard*
- *BBP has: - fewer collapses at 2%/200yr: **BBP 21 vs. 28 NGA***
  *- about **10% lower median collapse intensity***
  *- about **15% lower risk (MAF) of collapse***



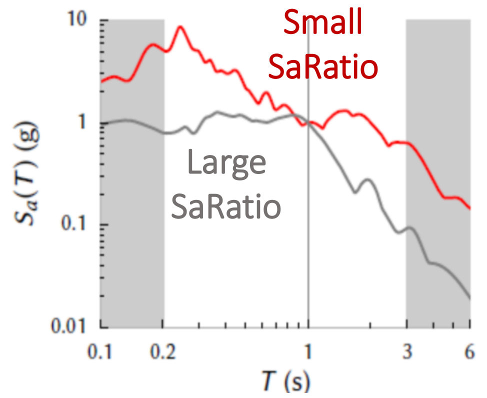
Multi-stripe Stripe Story Drift Response

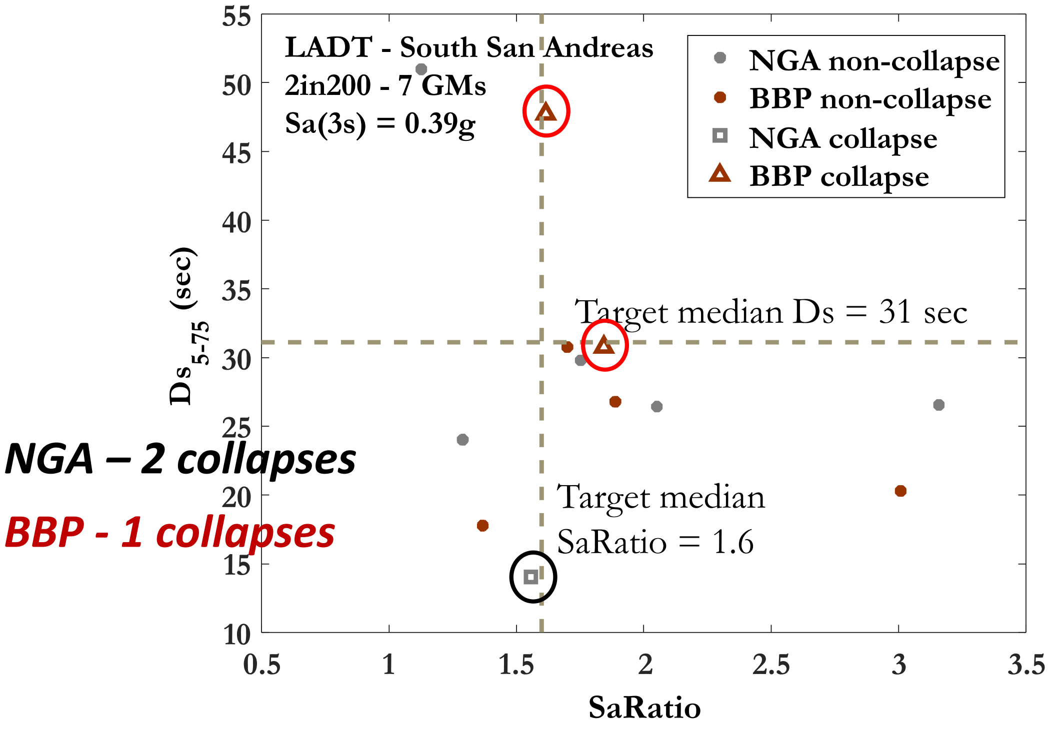


Collapse Fragility & Hazard Curves

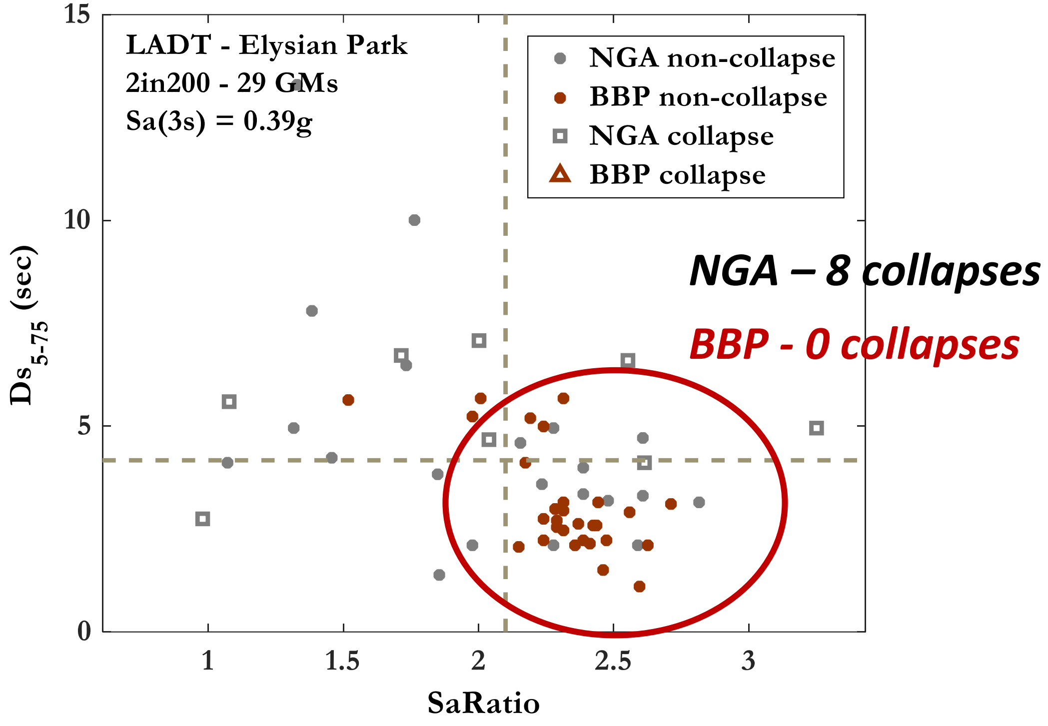
Collapse deaggregation: 20-story frame (LA Downtown)

- *Difference at 2%/200yr is checked source by source*
- *Collapse & non-collapse cases plotted vs. GM Spectral Shape & Duration*





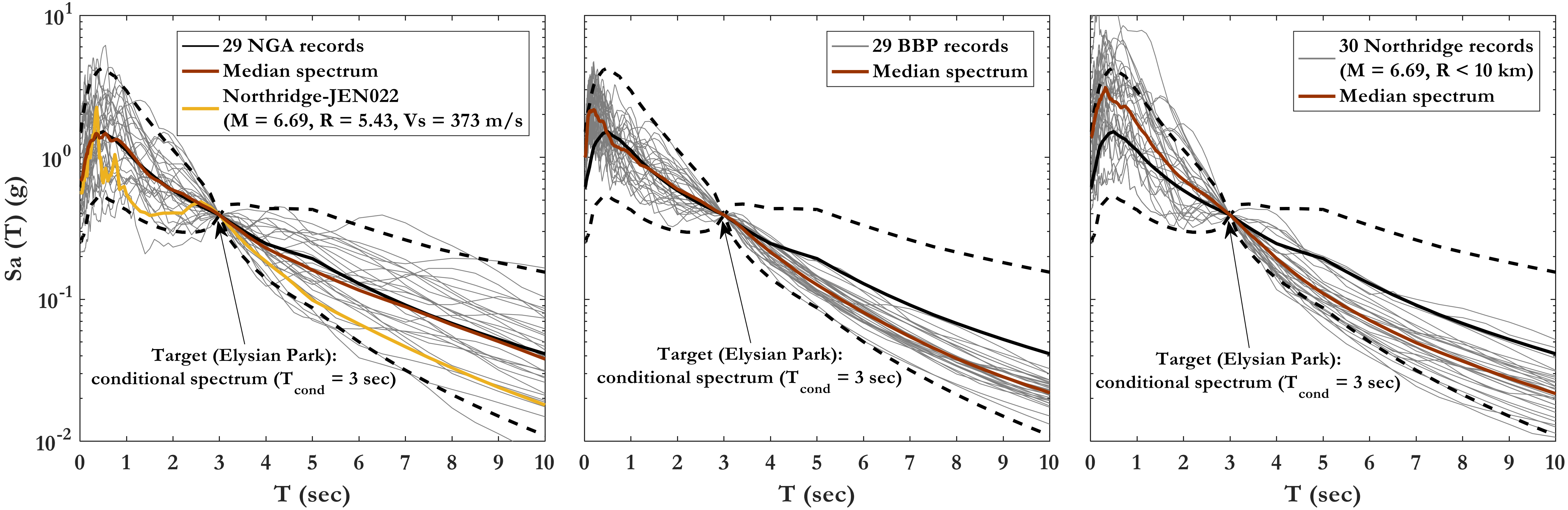
Southern San Andreas



Elysian Park

Elysian Park: NGA & BBP records versus Northridge records

- *NGA best match: median matches the target spectrum, but the only one Northridge differs*
- *BBP records: the long-period branch of median spectrum has steeper descent than the target*
- *Northridge records (w/ M & R): have similar trend with BBP simulation's but more high-frequency content*

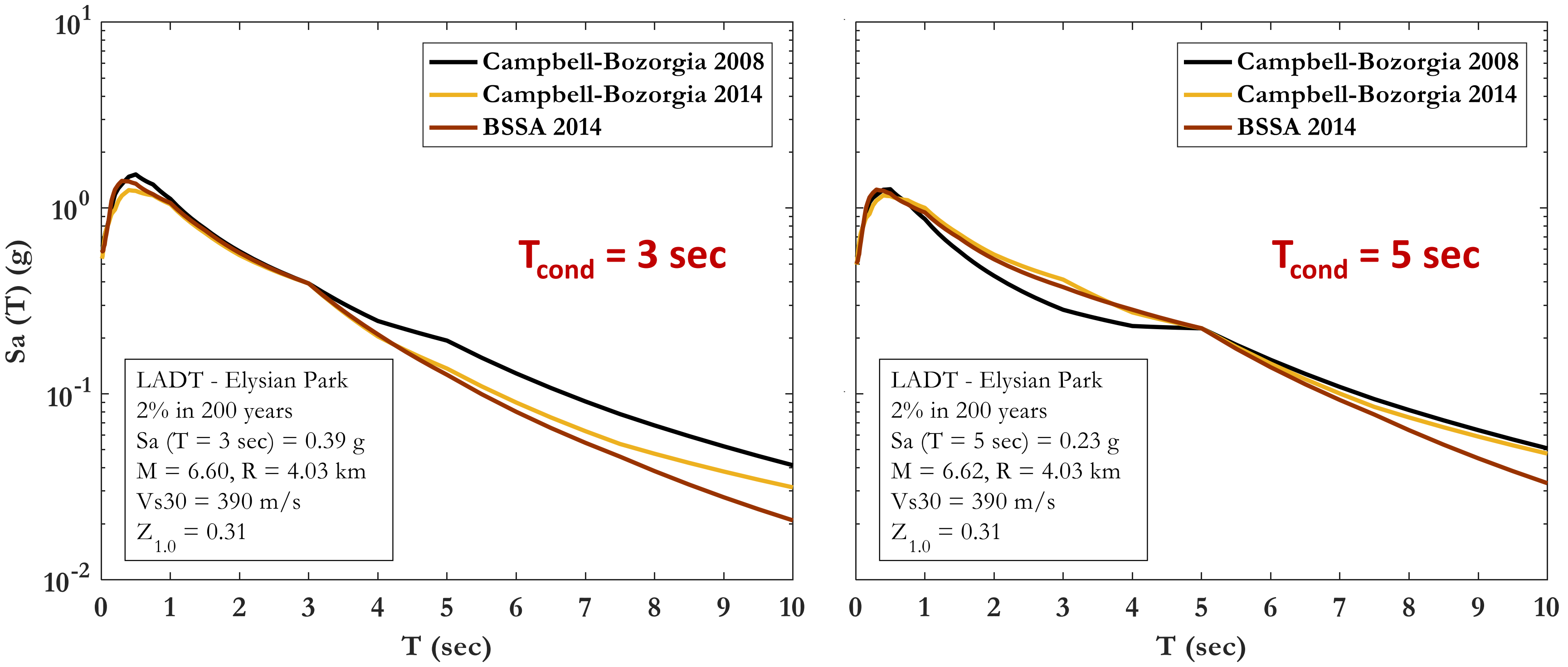


NGA match to GMPE target **BBP Elysian Park "match" to GMPE** **NGA Northridge records**

Selected records vs. target spectrum (2%/200yr, CB2008).
Seismic hazard deaggregation: Sa = 0.3925 g, R = 4.03 km, M = 6.60, contribution = 29.33%.
Target: CS (GMPE: Campbell-Bozorgnia 2008), Duration (Afshari and Stewart 2016).

Elysian Park: difference in GMPEs?

Seismic hazard deaggregation (for Elysian Park): M = 6.6, R = 4.0 km, Sa = 0.39 g



Conditional Mean Spectra by three GMPEs

Note: Hanging wall effect has been turned off in two CB GMPEs; BSSA (2014) - Boore, Stewart, Seyhan and Atksinson

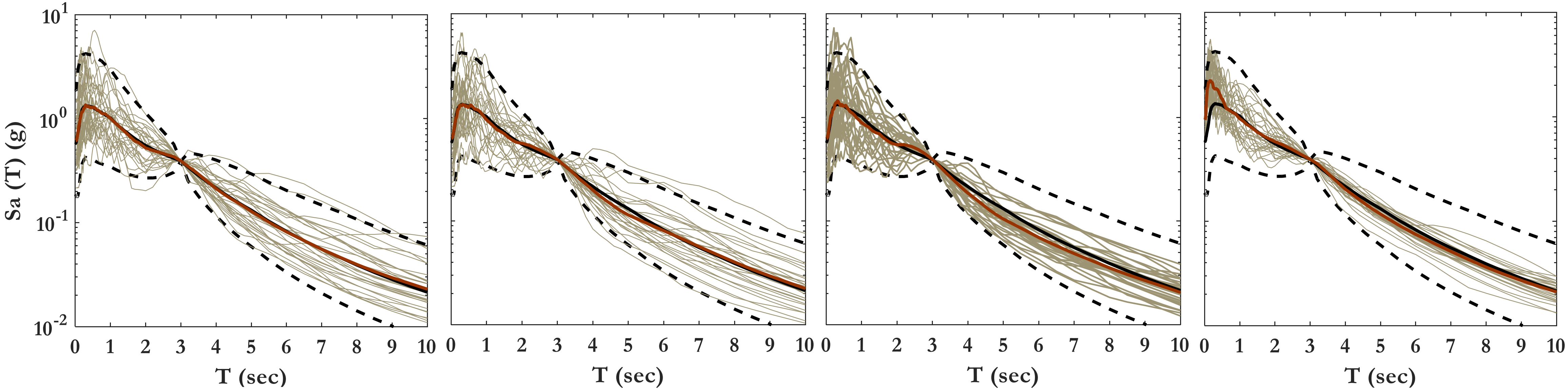
Reselect records by 4 schemes to BSSA 2014 target

NGA records
- *M: 6~8, R: 0~175 km*
- *Vs30: 198~629 m/s*
- *14 reverse-fault records (2 Northridge records)*
- *Maximum scaling: 29*

NGA (causal limits)
- *M: 6~7, R: 0 ~ 10 km*
- *Vs30: 195 ~ 585 m/s*
- *29 reverse-fault records (11 Northridge records)*
- *Maximum scaling: 23*

NGA (causal & scaling limits)
- *M: 6~7, R: 0 ~ 10 km*
- *Vs30: 195 ~ 585 m/s*
- *29 reverse-fault records (17 Northridge records)*
- *Maximum scaling: 5*

BBP records
- *M = 6.60, R ~ 4.03 km*
- *Vs30 ~ 390 m/s*
- *Maximum scaling: 5*



Comparison of selected records (T_{cond} = 3 sec) by BSSA-2014 for Elysian Park (2%/200yr).

20-story frame collapse by reselect records by 4 record suites

NGA records
- *M: 6~8, R: 0~175 km*
- *Vs30: 198~629 m/s*
- *14 reverse-fault records (2 Northridge records)*
- *Maximum scaling: 29*

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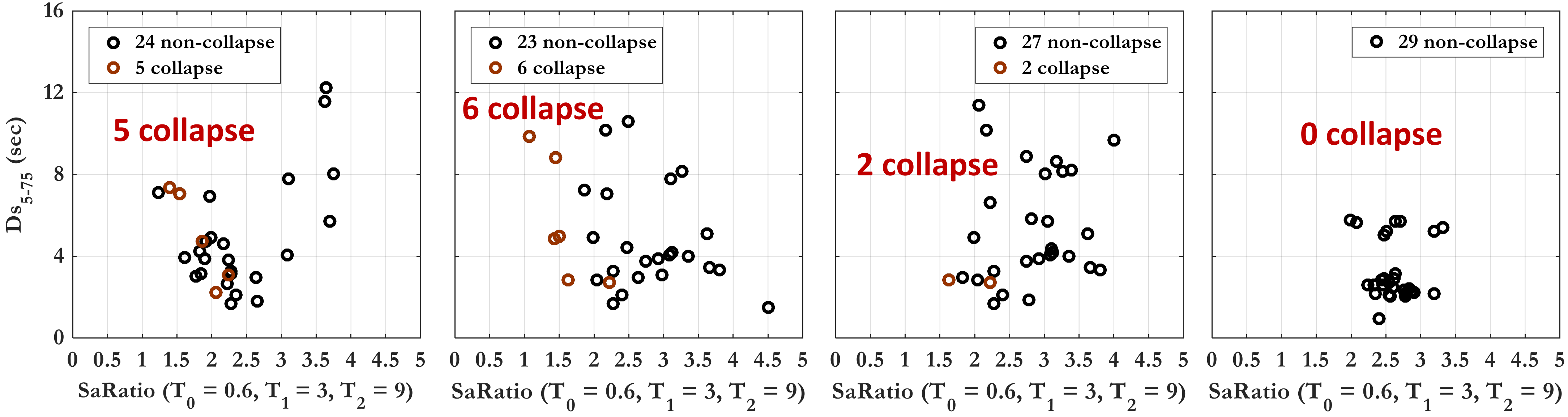
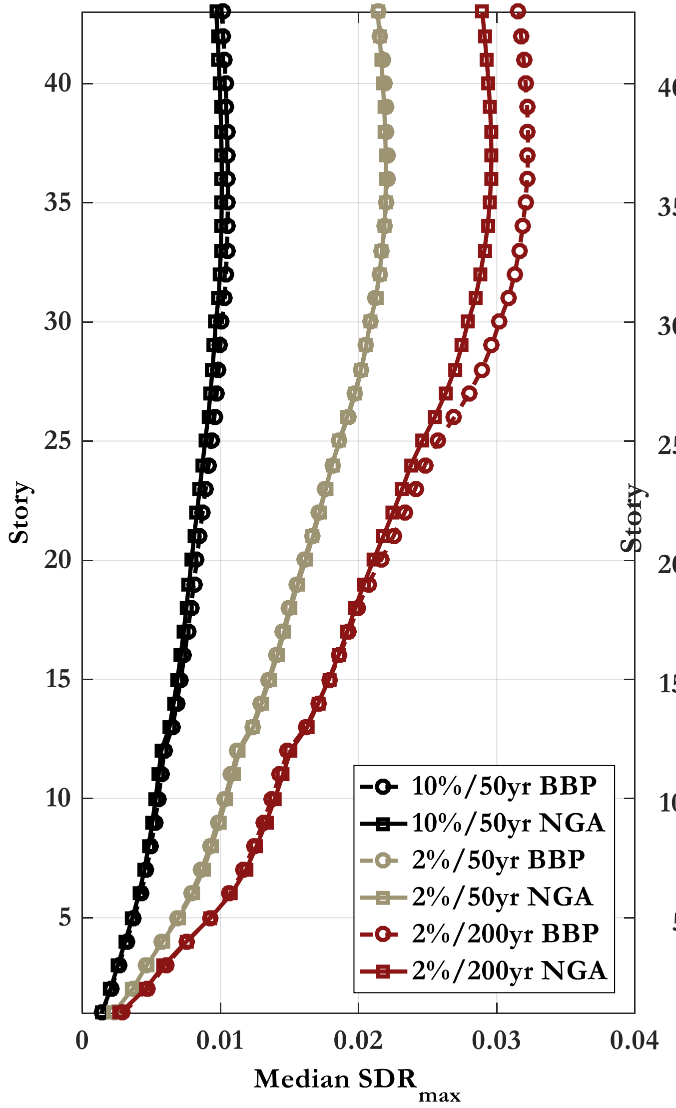
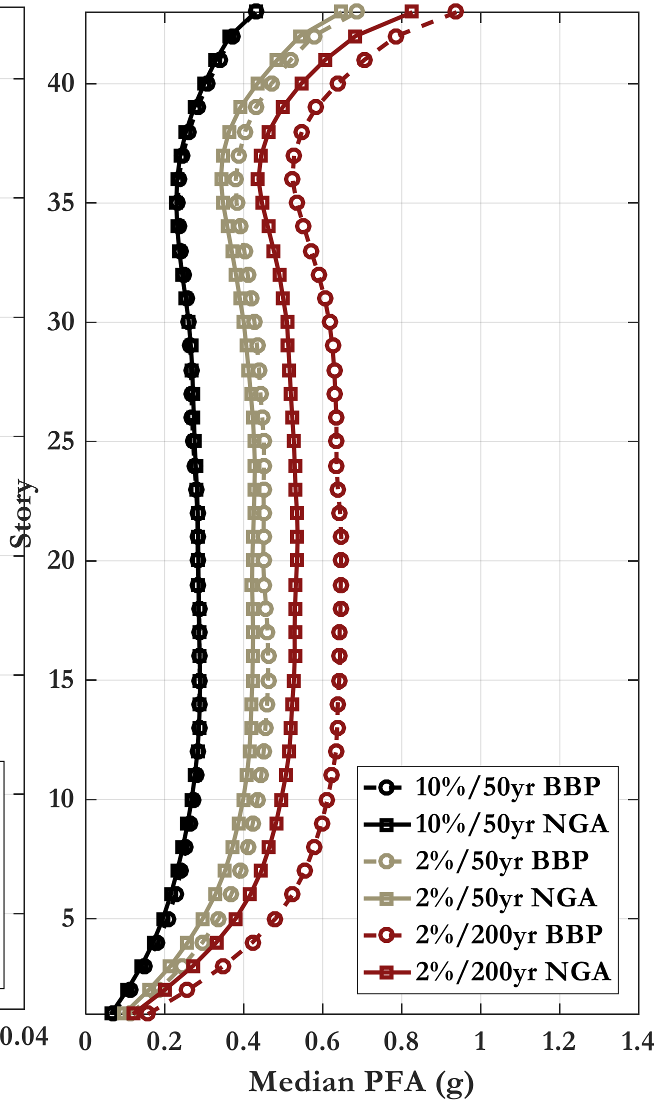


Comparison of building collapses (T_{cond} = 3 sec, Elysian Park, 2%/200yr).

42-story shear wall building (LADT)

- *No statistical difference up to 2% in 50 yr*
- *~10% difference under 2% in 200 yr*





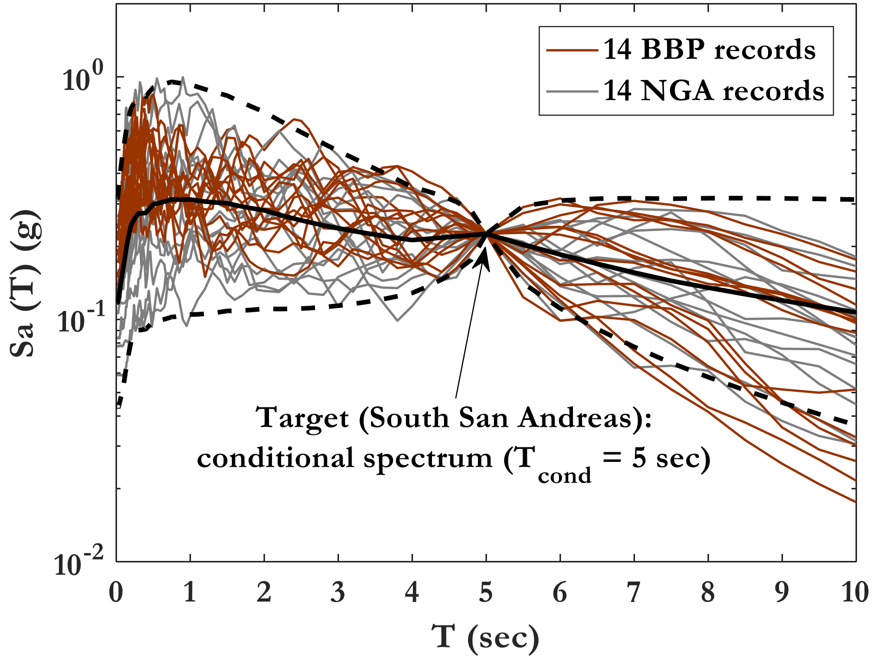
SDR_{max} **PFA**

Median structural response demands

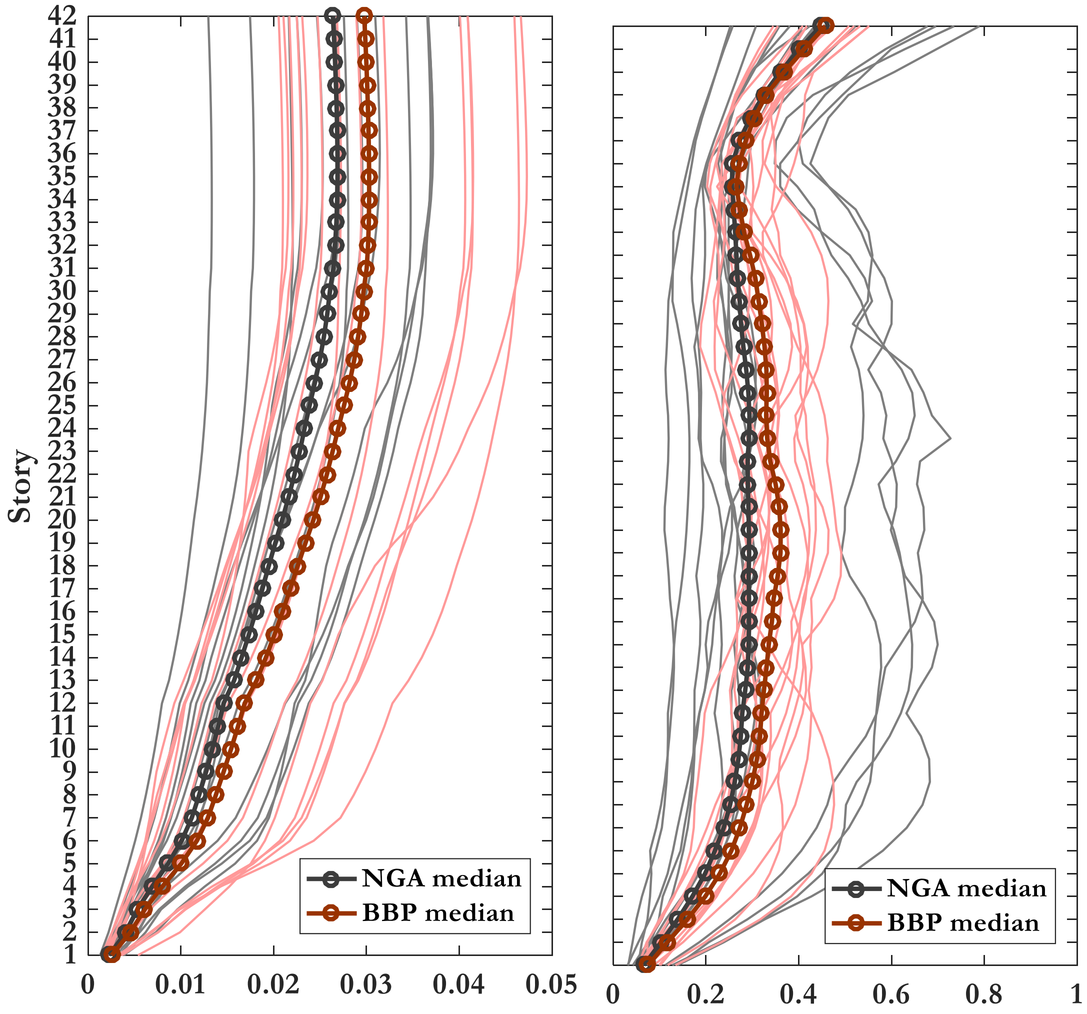
42-story shear wall building (LADT)

San Andreas responses: BBP vs. NGA

- *No difference in estimated median responses*
- *Less dispersion in BBP results*



2%/200yr hazard-level **South San Andreas motions (14% of LADT seismic hazard)**



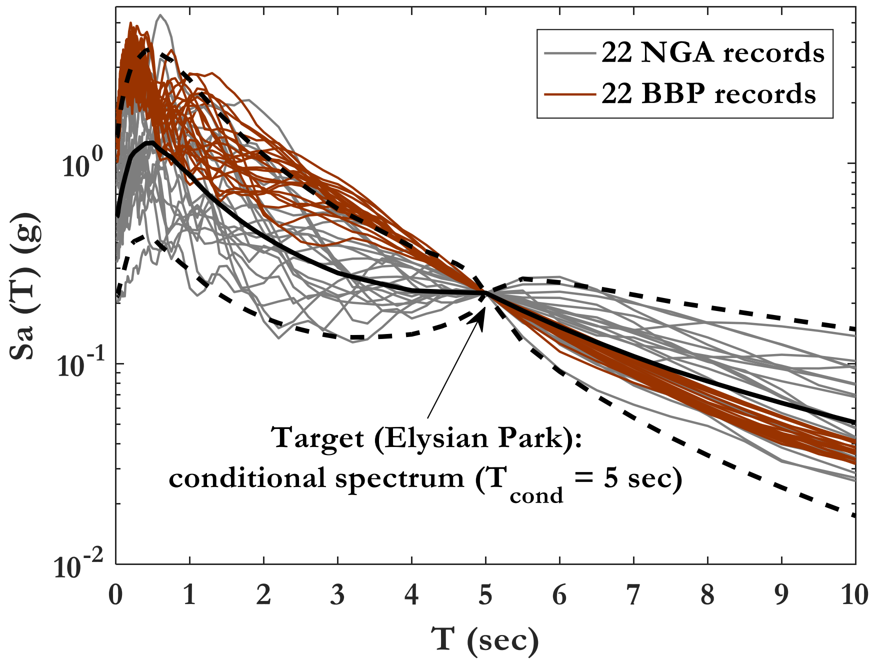
SDR_{max} **PFA**

Structural responses under 14 NGA and BBP records

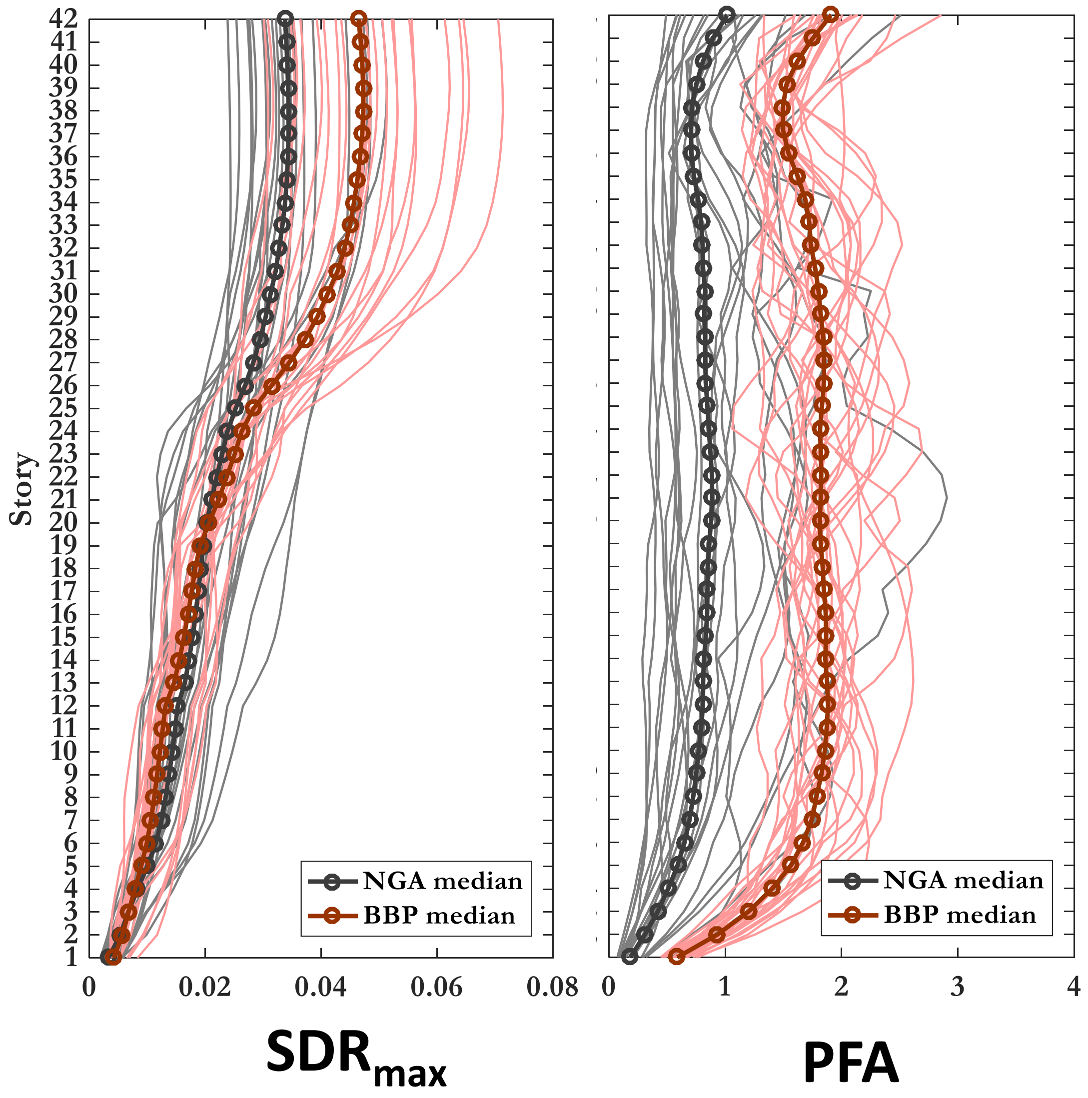
42-story shear wall building (LADT)

Elysian Park responses: BBP vs. NGA

- *BBP records -- higher structural demands*
- *Higher-mode story drifts*
- *Higher-frequency Sa's and PFA*



2%/200yr hazard-level **Elysian Park motions**
(22% of LADT seismic hazard)



Structural responses - 22 NGA and BBP records

Summary (LADT Site)

At 10%/50yr & 2%/50yr level (similar to SF downtown):

1. Simulated (BBP) motions can be selected/scaled to match the PSHA target IMs (CS+D_{s5-75}) with *much smaller scaling than existing recorded motions.*

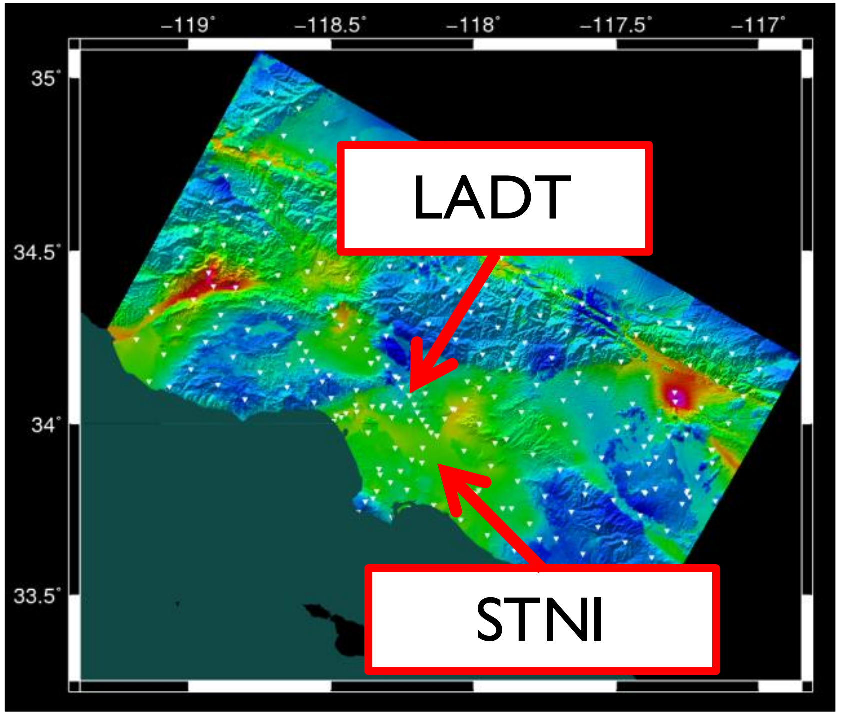
2. When ground motions are selected/scaled to comparable target IMs, there are no statistically significant differences in *calculated structural responses and collapse risks between recorded and simulated motions.*

At 2%/200yr level:

1. *Limitations in our knowledge about rare earthquakes*
2. *The 4 paralleling case studies for Elysian Park scenario indicates that increasing causal and scaling constraints on NGA leads to:*
   - *more difficulty matching GM's to target spectra*
   - *selected records tend to be more "local"*
   - *structural responses tend to converge toward BBP record response*
3. *Importance of high-frequency content for tall buildings: higher-mode drifts, PFA*

Engineering Utilization of Cybershake (3D) Motions

Conventional (PSHA w/recorded GMs) vs. 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

3D Simulations

- Velocity Profile (SCEC CVM-S 4.26)
- Wave Propagation

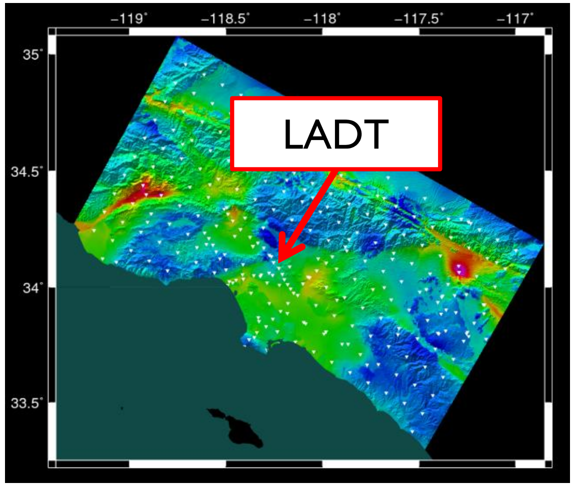
Physics Based & Stochastic (BB)

- Physics Based T > 1second
- Splicing period ~1 second

PSHA Approach

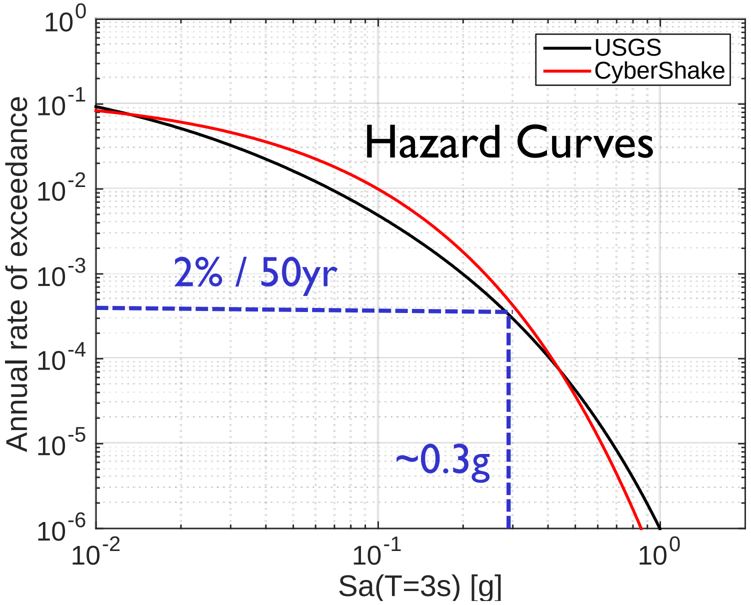
- Multiple ruptures following UCERF 2
- Faults within 200 km

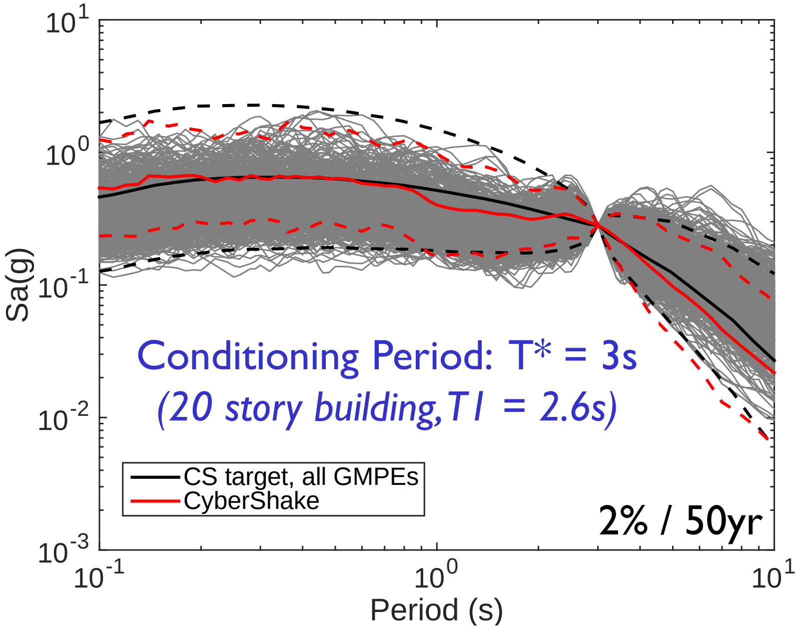
Direct Simulation with CyberShake

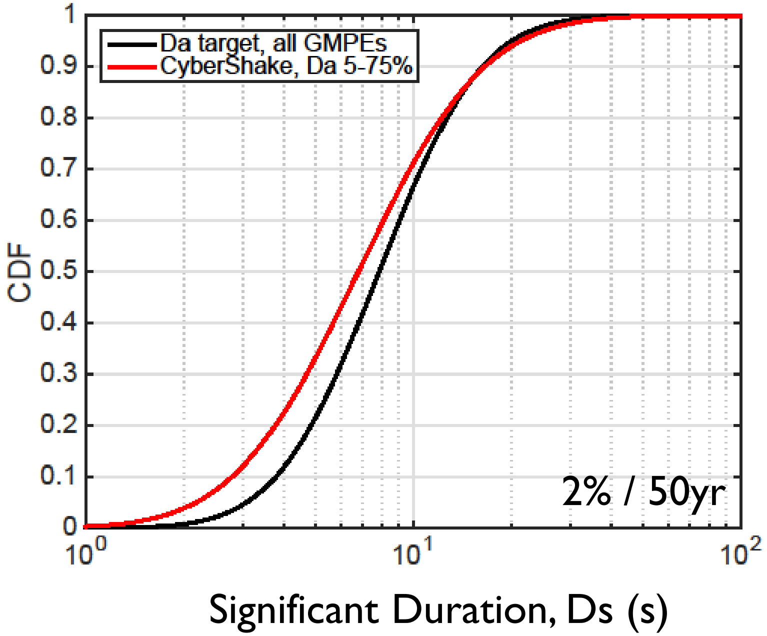


Comparison – CyberShake and Conventional PSHA

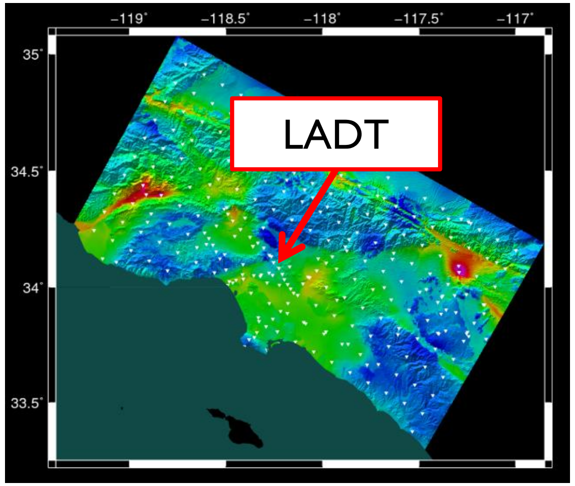
- hazard curve *(Sa for T = 3s)*
- ground motion CS *(Sa, T* = 3s, multiple return periods)*
- ground motion Ds *(multiple return periods)*

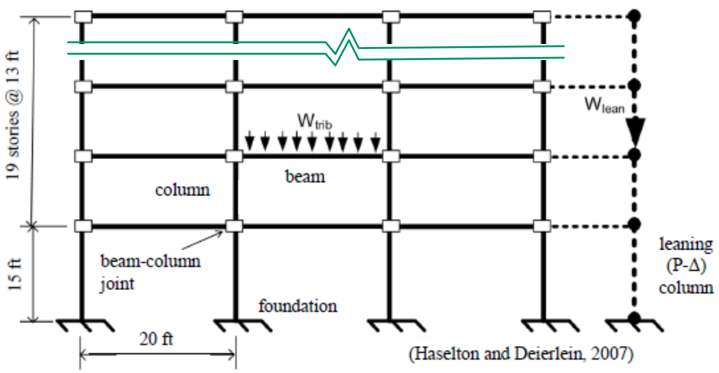






Direct Simulation with CyberShake

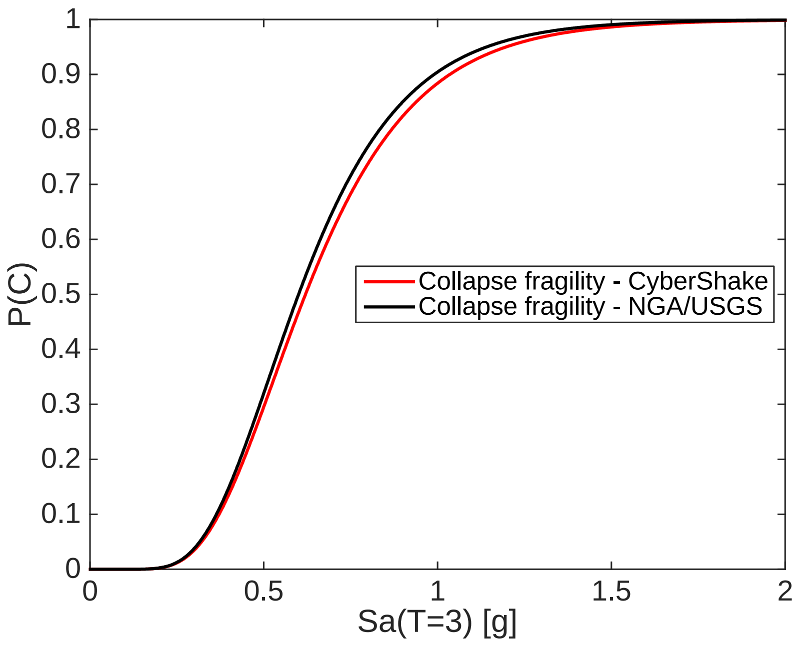




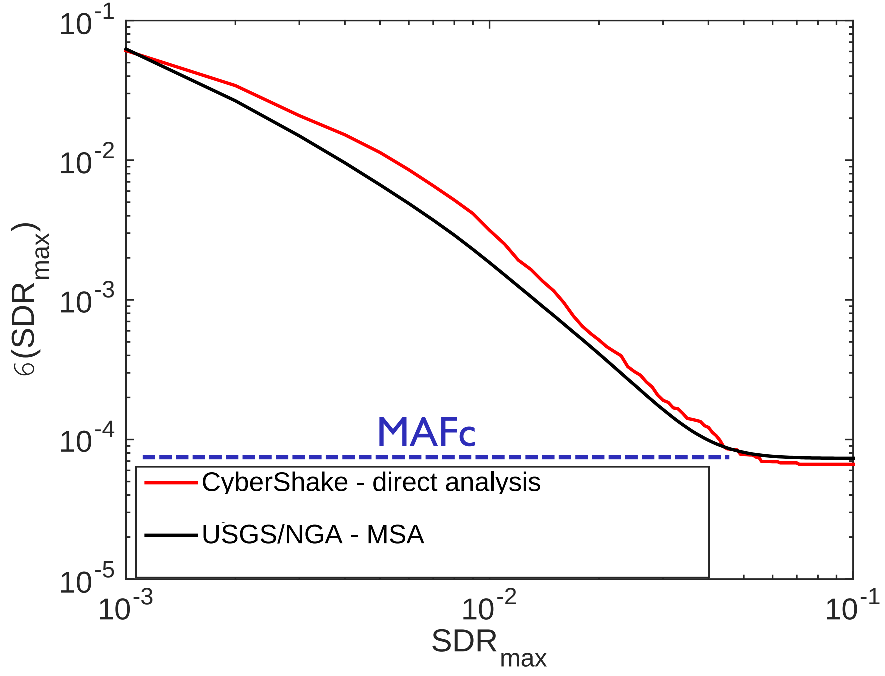
20-story building, T_1 = 2.60s

Structural Response Comparisons

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

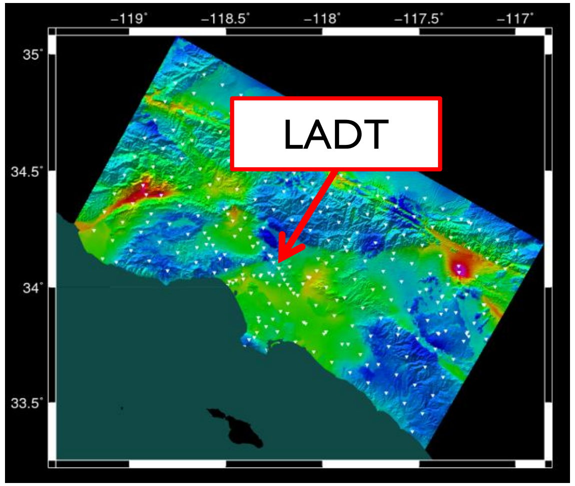


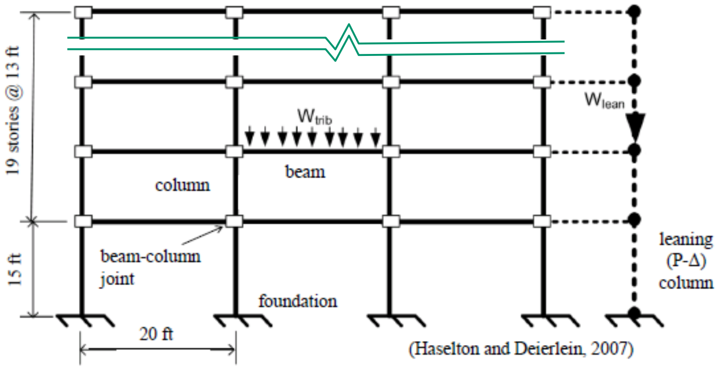
Collapse Fragility



Story Drift Exceedence

Direct Simulation with CyberShake

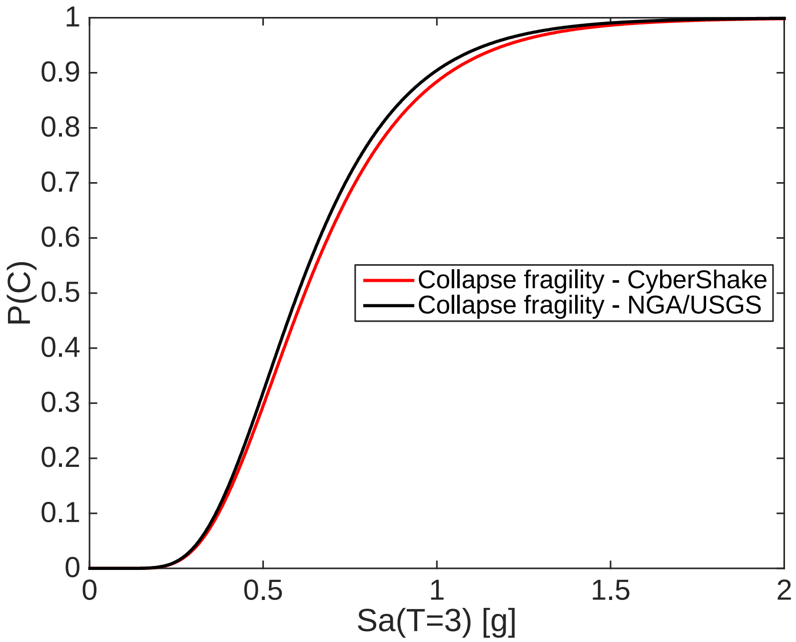




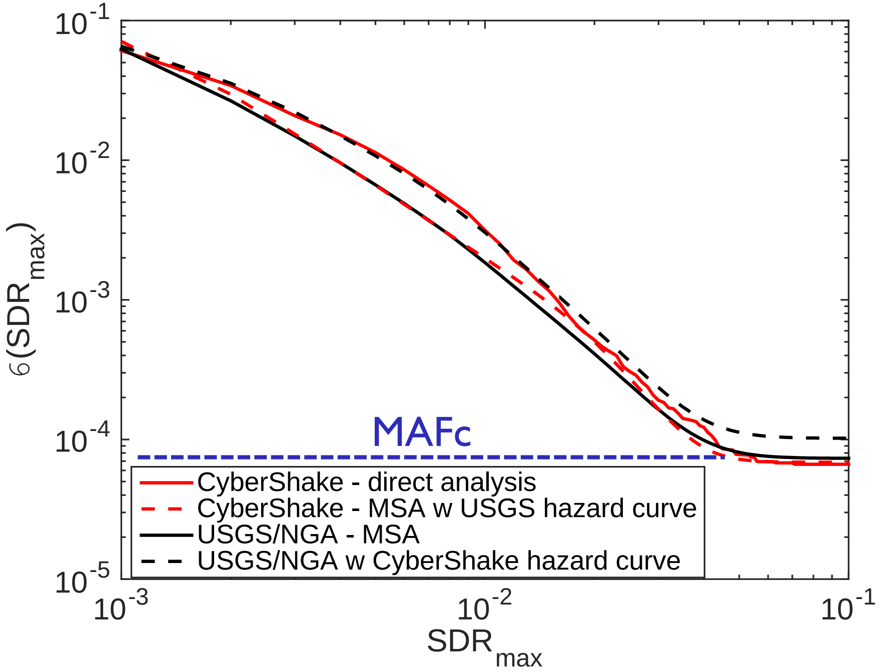
20-story building, T_1 = 2.60s

Mix and Match: ground motions with hazard curves

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

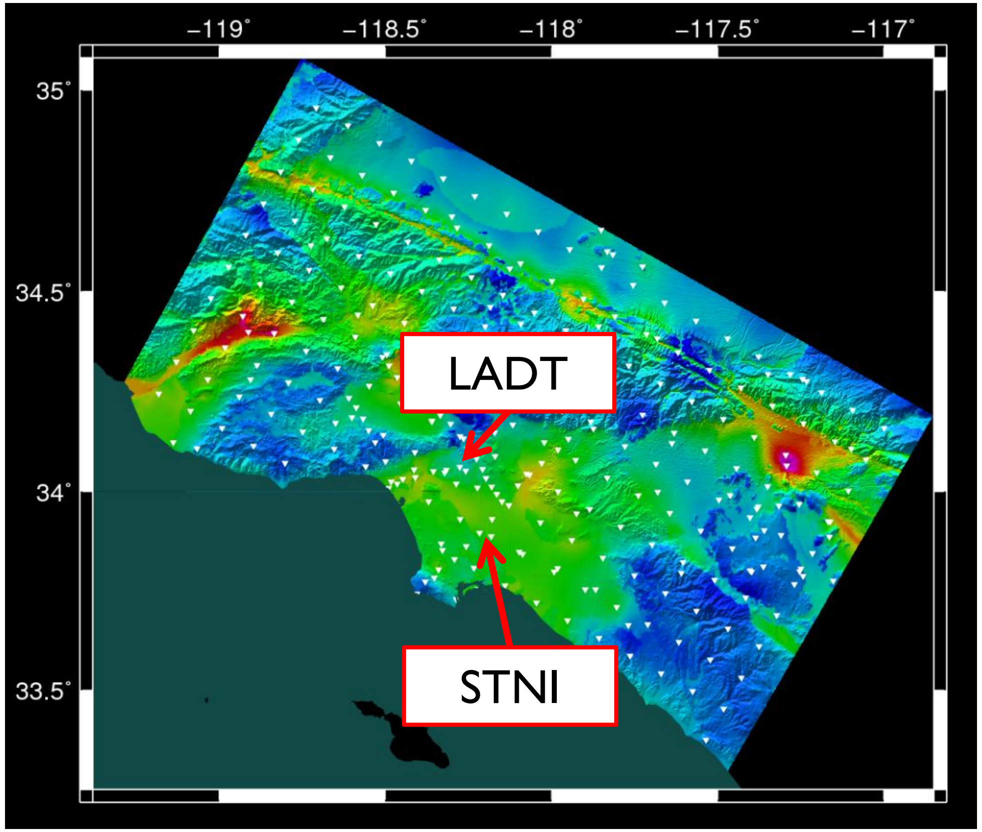


Collapse Fragility



Story Drift Exceedence

Direct Simulation with CyberShake



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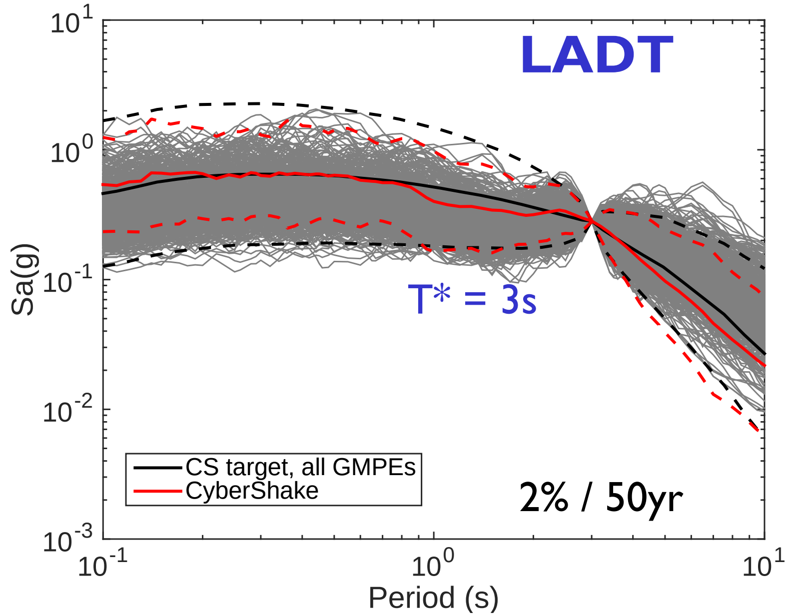
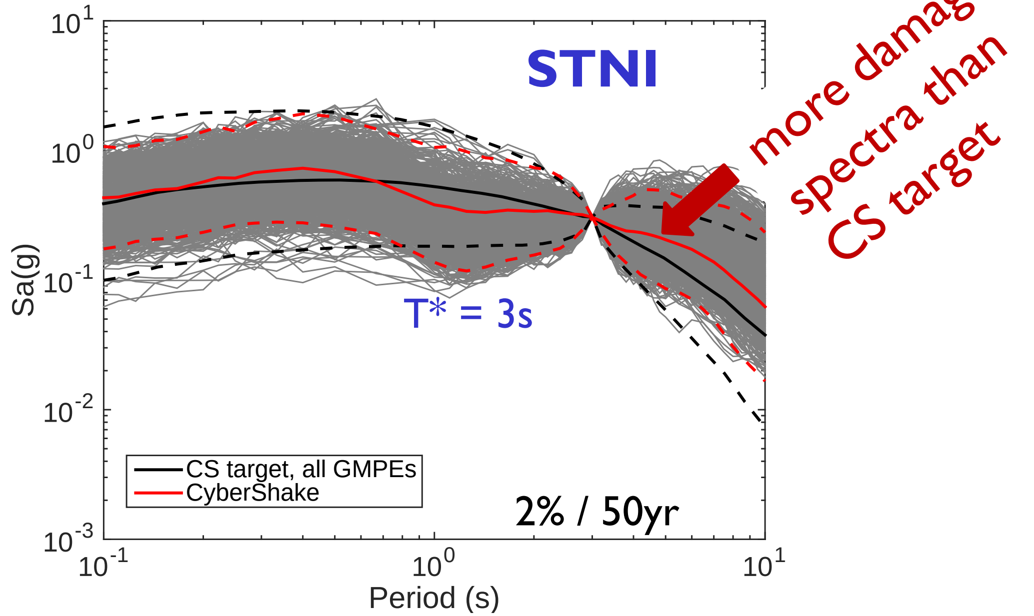
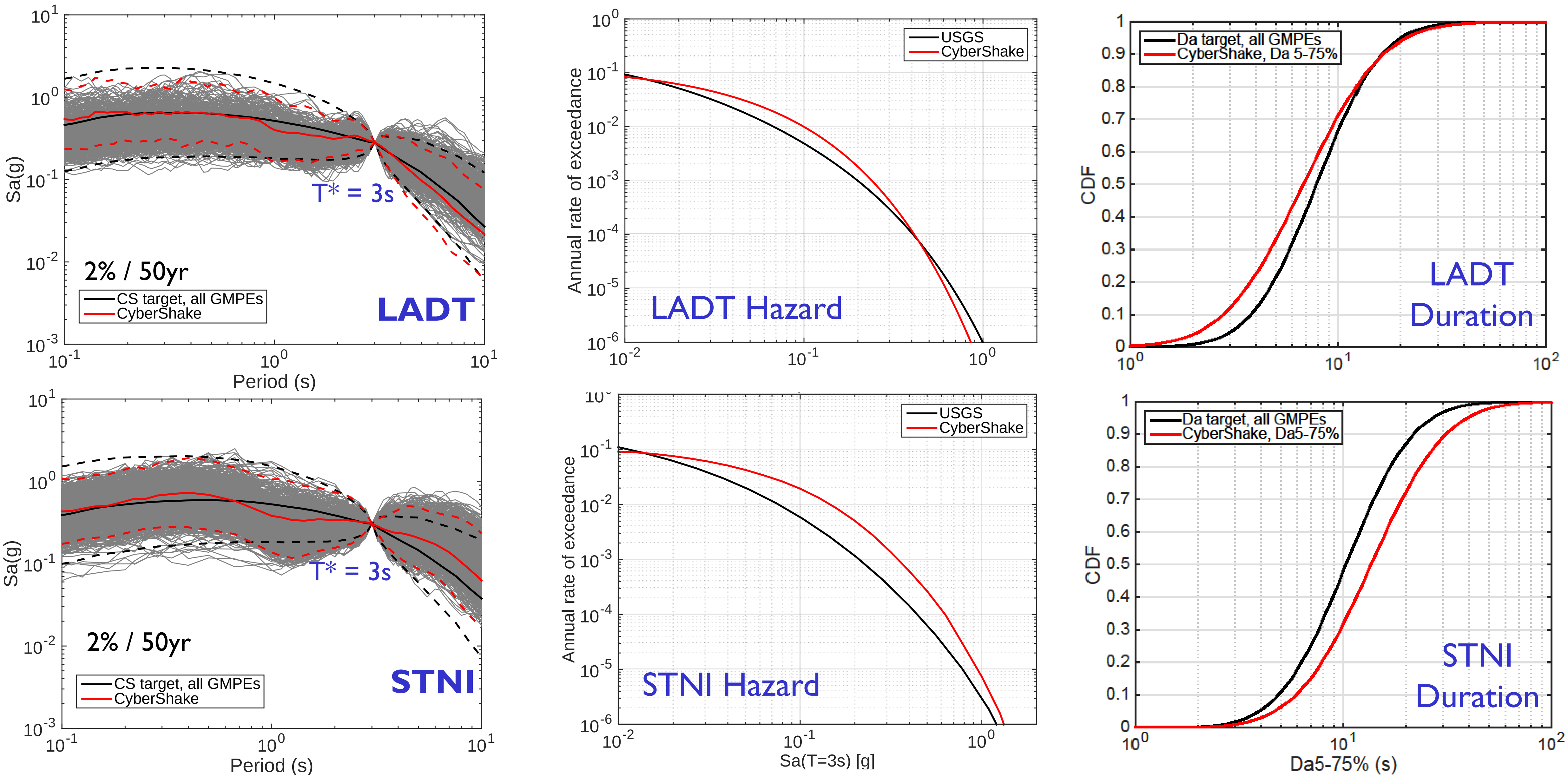
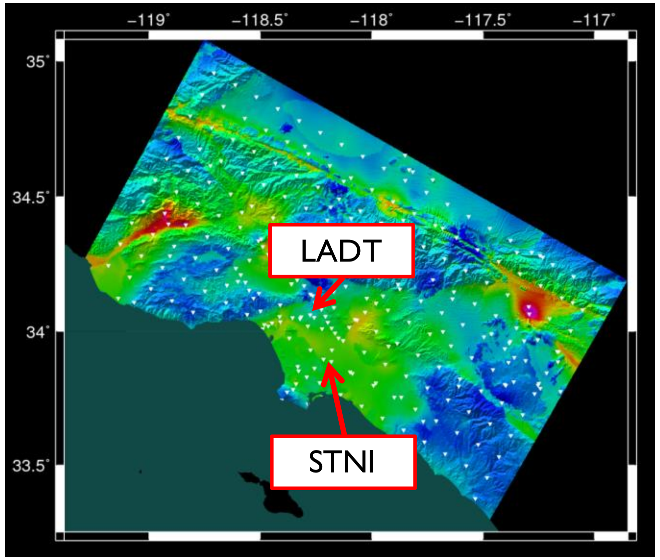


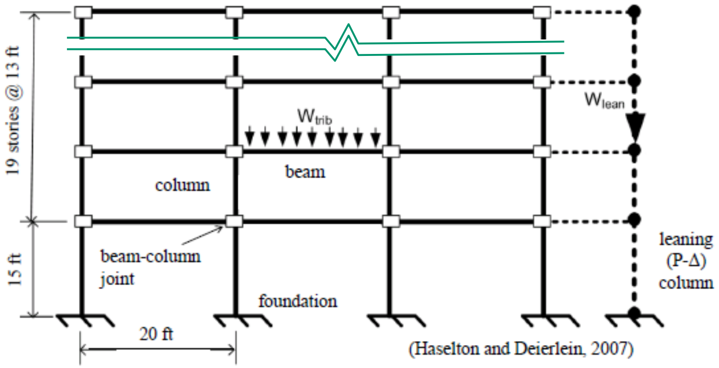


Direct Simulation with CyberShake

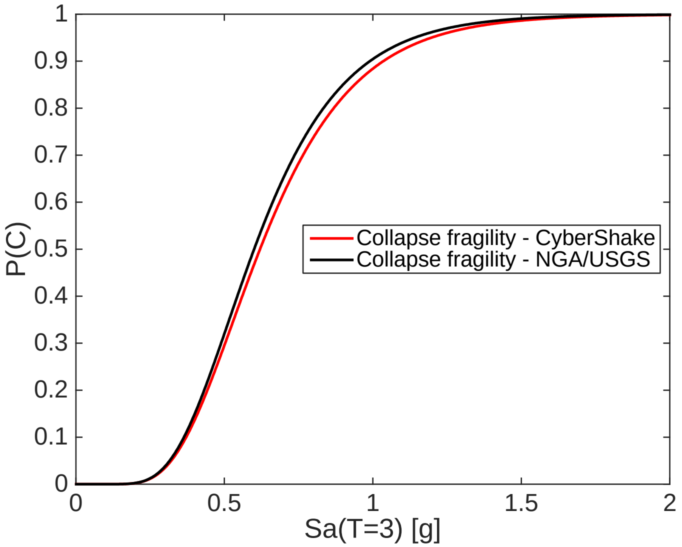


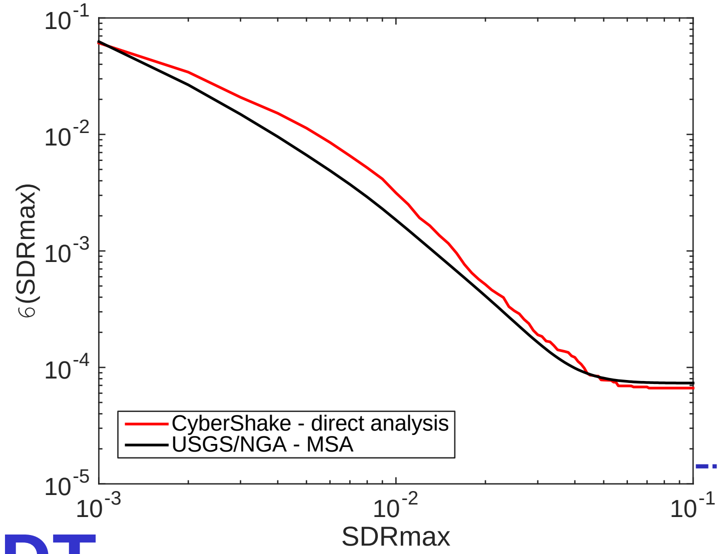
CyberShake: LA downtown vs STNI sites



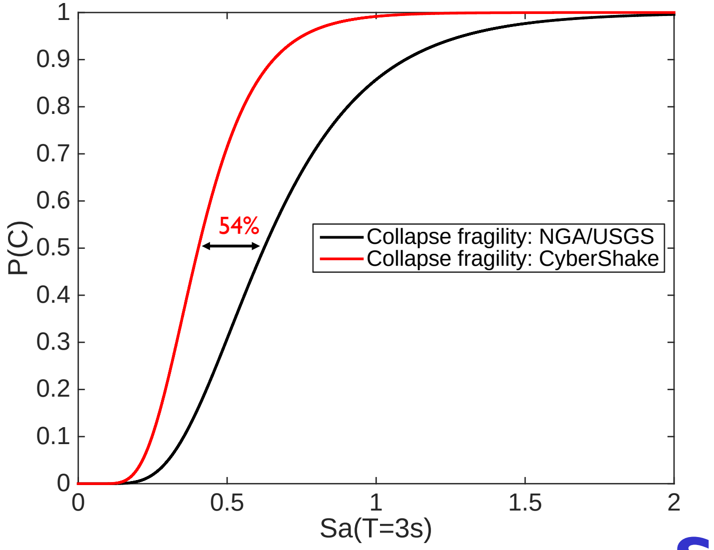


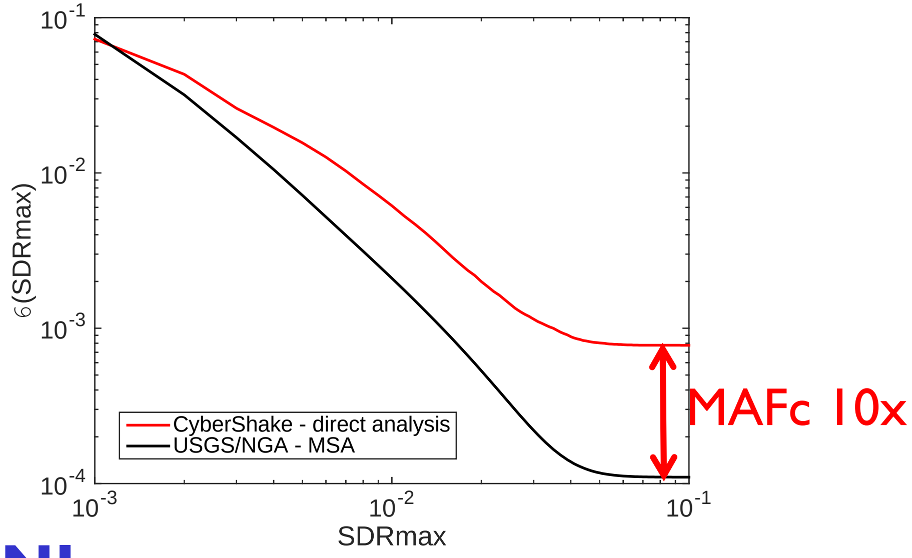
20-story building, T_1 = 2.60s





LADT



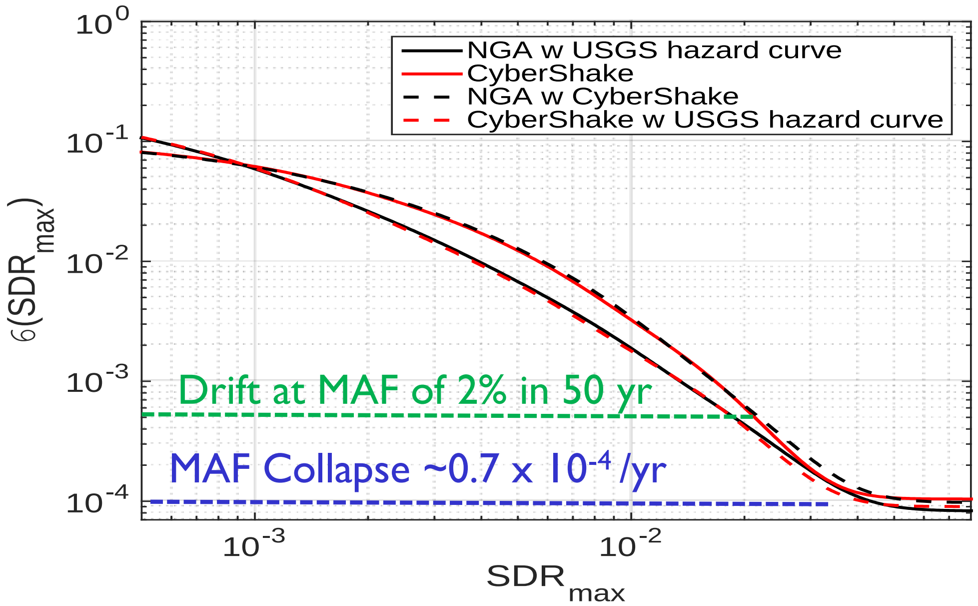


STNI

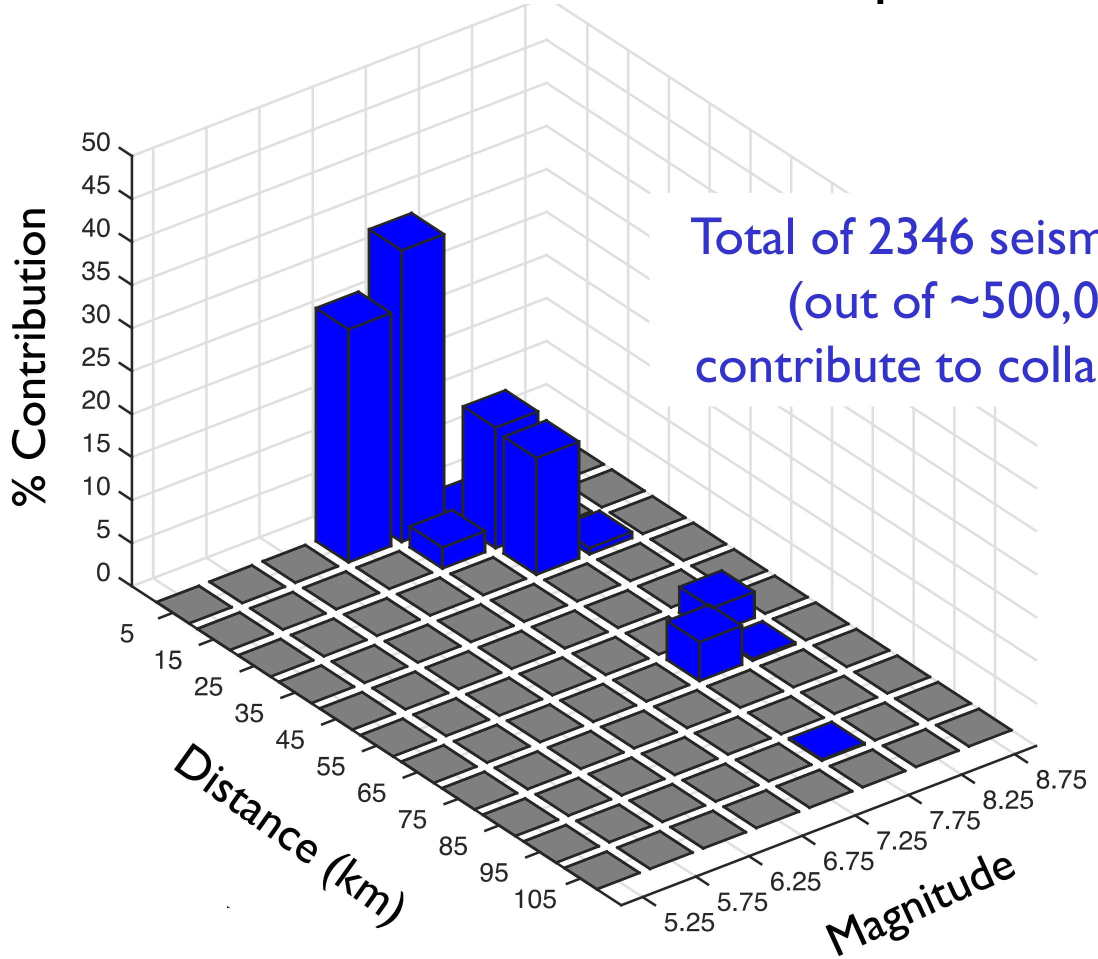
Collapse Fragility

Story Drift Exceedence

CyberShake: Deaggregation of Risk

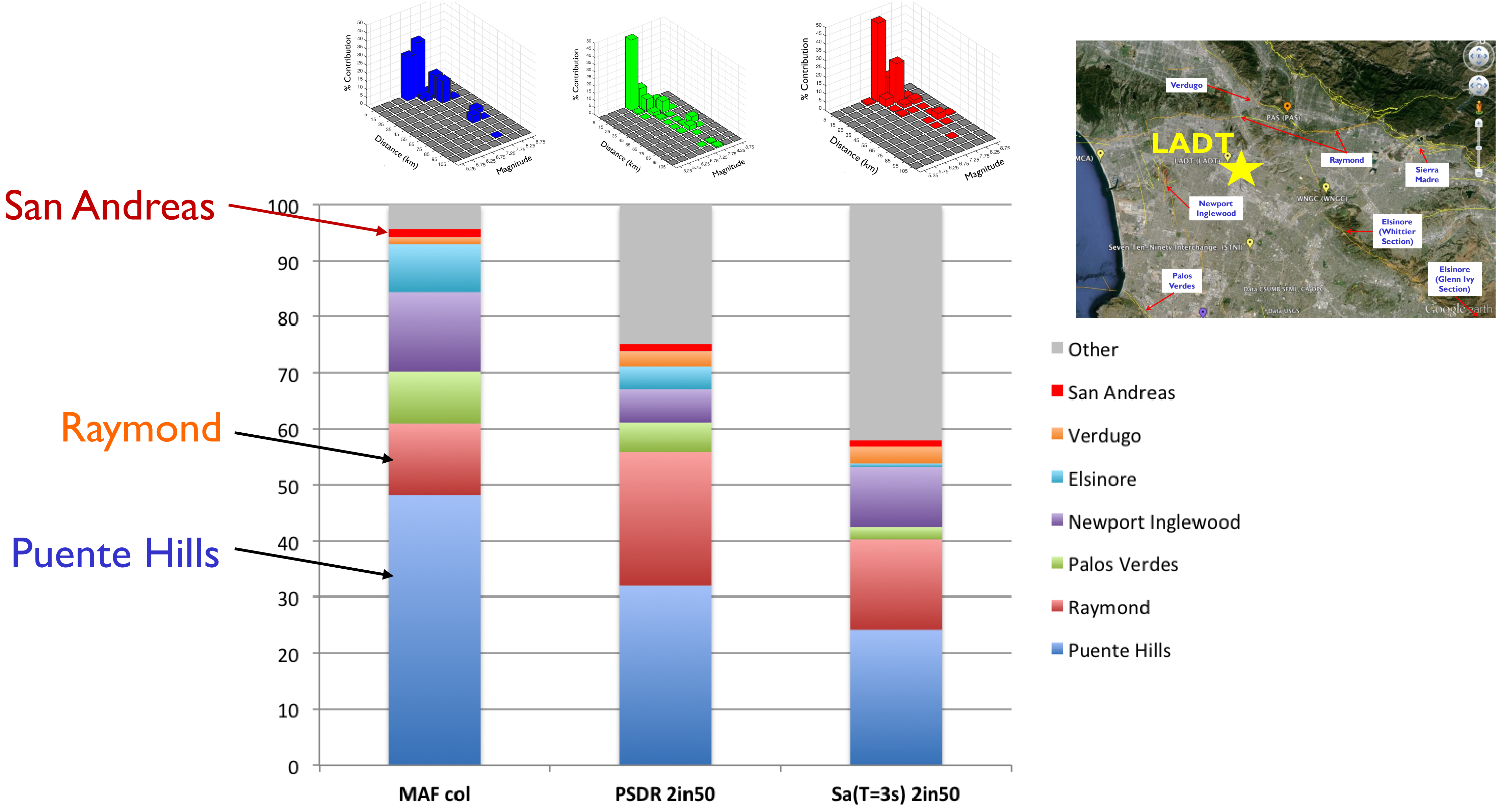


Deaggregation of Risk:
Which earthquake faults and rupture realizations most contribute to collapse?



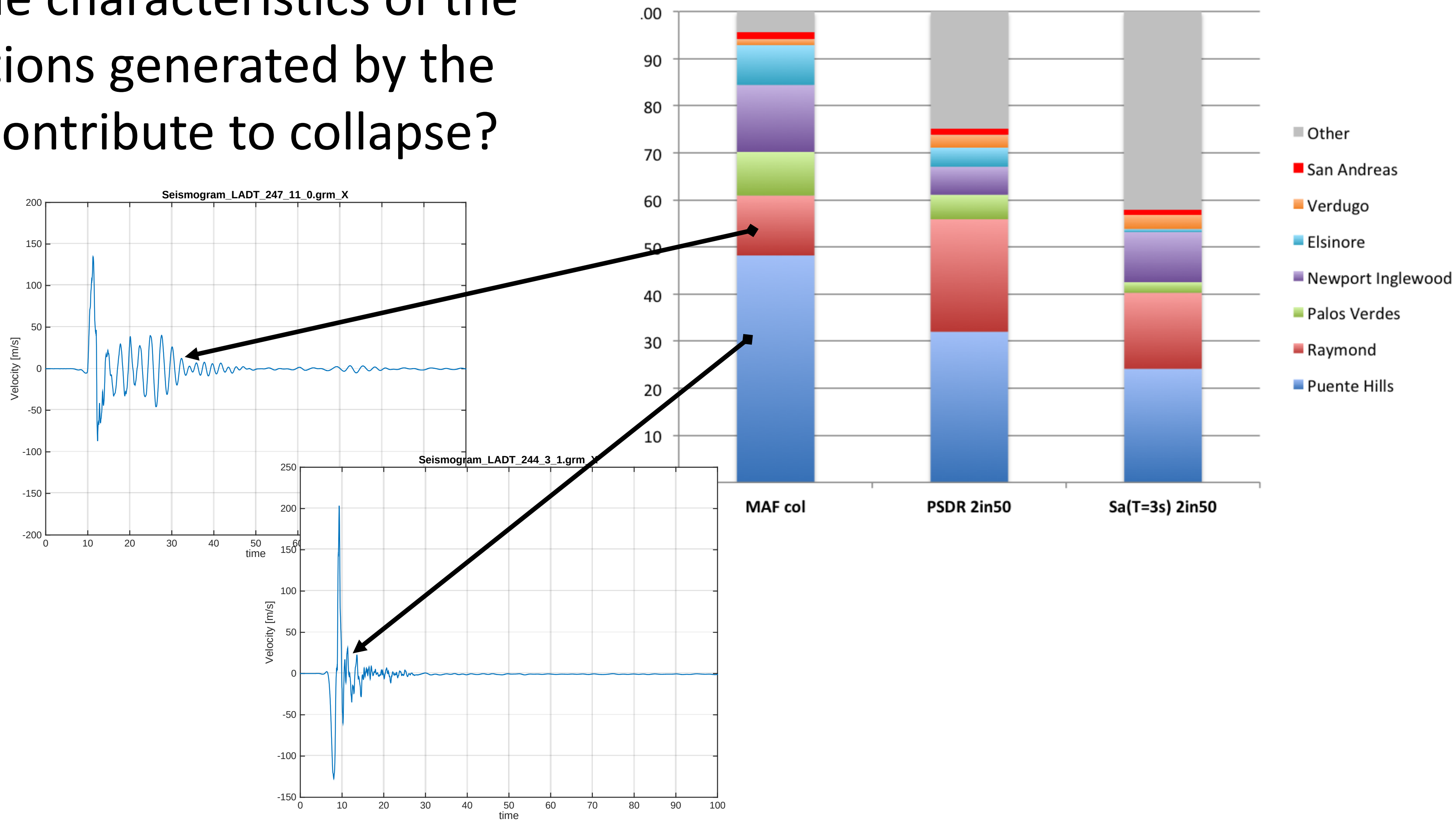
Total of 2346 seismograms (out of ~500,000) contribute to collapse risk

CyberShake: Deaggregation of Risk versus Hazard



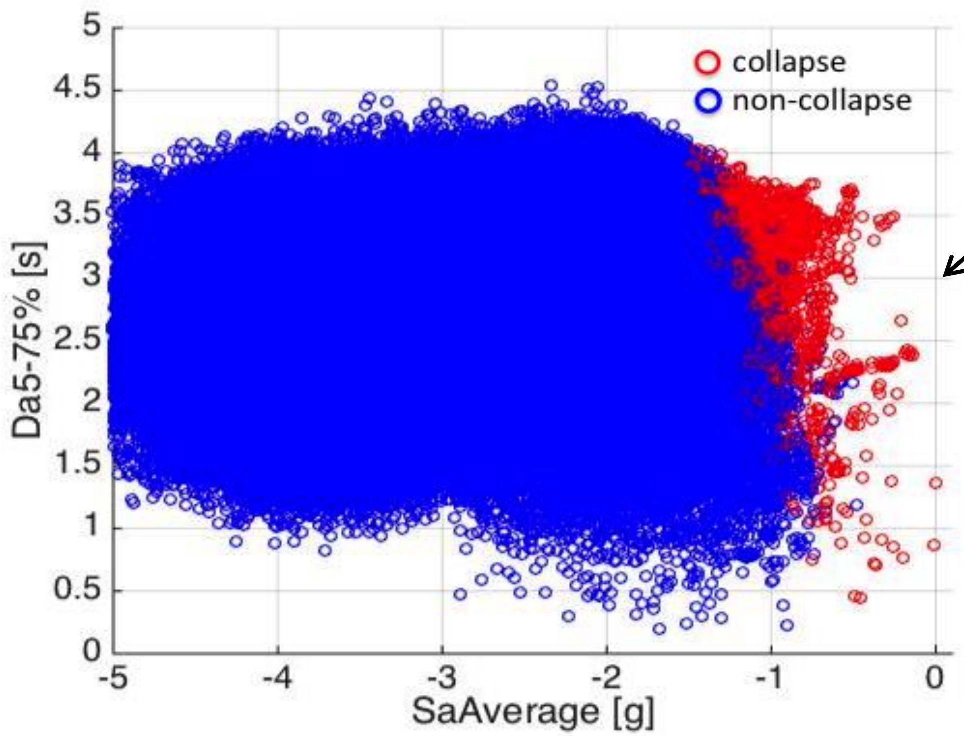
CyberShake: Characterization of Damaging Ground Motions

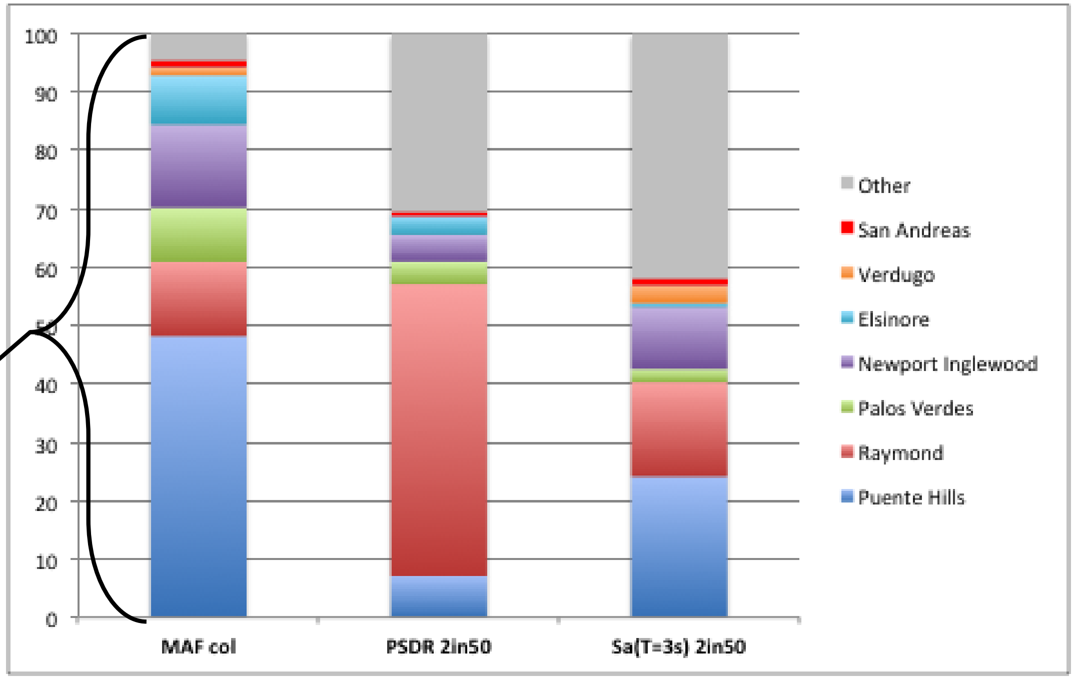
What are the characteristics of the ground motions generated by the faults that contribute to collapse?



CyberShake: Characterization of Damaging Ground Motions

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.

Concluding Thoughts

- Utilization of Simulated Motions
  - IF records are selected and scaled to comprehensive targets (Sa, CS, Ds, correlation/skew), the resulting response is similar between recorded and simulate motions
  - BBP motions and GMPE targets match well up to: 2/200yr - SF, 2/50yr - LADT, 10/50 – SB
  - **Simulated GM's (based on representative events) require less scaling; considered to be more realistic**
  - ASCE 7 emphasis on causal features (fault type, M,R..) and scaling limits help to capture GM characteristics, BUT limit the number of available GM's
- 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 near fault M; basin effects, directivity, etc.).
- Continuing studies
  - Quantitative validation is important, but can only go so far
  - Role of risk deaggregation and sensitivity studies to highlight important features of EQ simulations
  - More education and transparency in confidence in models and assumptions