Characterization of basin effects for seismic performance assessments of tall buildings using CyberShake simulations

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1. Introduction

To explore areas where simulated ground motions provide unique advantages over recorded motions for performance-based engineering, this work focuses on basin effect characterization in seismic hazard and risk assessments of tall buildings. Basin effects are among the most prominent features of regional geology that can be more reliably captured by 3D physics-based earthquake simulations as compared to more empirical methods using ground motion prediction equations (GMPEs).

We conduct (1) direct analysis with around one million nonlinear response analyses using simulated seismograms and physics-based probabilistic seismic hazard analysis (PSHA) from CyberShake simulations, in contrast to (2) performance assessment with conventional methods using recorded motions from PEER NGA database and PSHA from US Geological Survey. Investigation of direct analysis using CyberShake simulations enables deaggregation of building collapse risk to examine (1) relative contributions of earthquake ruptures and (2) waveform properties of damaging motions. Based on these insights, ground motion archetypes are formulated to represent long-period cyclic features. To gauge the effect of unique archetype features on structural response, we develop spectrum- and duration-equivalent sets of "basin" and "non-basin" ground motions to compare collapse fragility. Finally, we propose novel metrics - termed duration and sustained amplitude adjusted response spectra - to characterize damaging features of basin motions that contribute to collapse.

2. Case study building

The building used in this study is an archetype model of a 20-story reinforced concrete special moment frame (Fig. 1) that is representative of office buildings in California. The 20-story building was designed according to the governing provisions of the 2003 IBC, ASCE7-02 and ACI 318-02. The frame is idealized as a 2D analysis model using OpenSees, where the first three modal periods are 2.63s, 0.85s and 0.45s. The nonlinearities are captured in concentrated plasticity models in panel zones and plastic hinges at the ends of columns and beams. Lumped plastic hinges are modeled using the phenomenological Ibarra-Medina-Krawinkler model, which has been previously calibrated to capture the deterioration of concrete members out to large deformations. Rayleigh damping of 5% critical is assigned to periods T_1 and $0.2T_1$, where T_1 is the period of the fundamental mode.

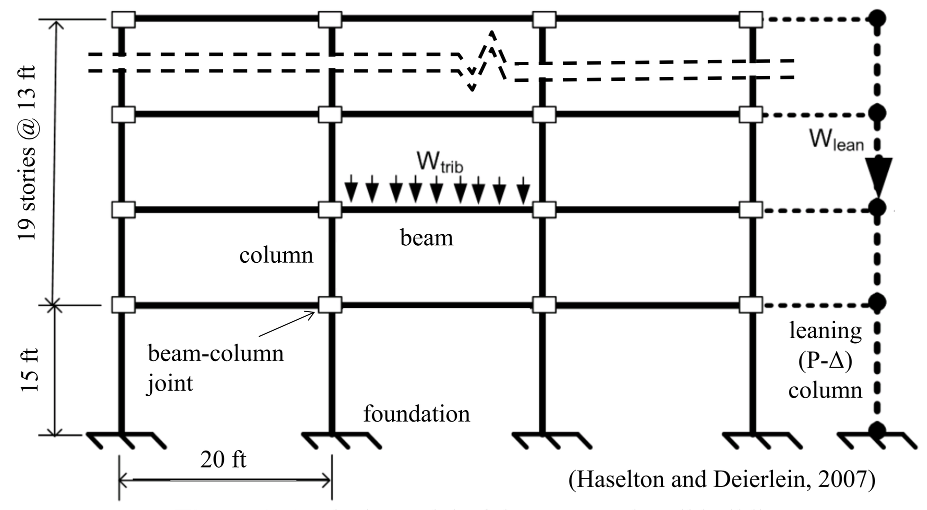

Figure 1. Analysis model of the case-study tall building.
Model periods: T_1 = 2.63s; T_2 = 0.85s; T_3 = 0.45s

3. Comparative assessments of seismic performance – CyberShake vs. "conventional"

Presence of sedimentary basins is well recognized for potential detrimental effects on buildings, but their quantification is elusive due to limited availability of recorded motions. With a broader goal of exploring the areas where simulated earthquakes can offer unique engineering insight, we examine seismic performance of a 20-story building for two sites located in the Los Angeles basin (Fig. 2). Building performance is estimated using (1) a full simulation approach, where the site-specific hazard information (Fig. 3) and ground motions (Fig. 4) are obtained from the CyberShake simulations, and (2) a conventional approach, relying on PSHA from USGS (Fig. 3) coupled with NGA recorded motions. In terms of tall building seismic demands (Fig. 5), the two approaches yield similar estimates for Los Angeles downtown, LADT, where many tall buildings are located, but produce drastically different results for a deep basin site, STNI.

CyberShake sites	LADT	STNI
Site information		
Latitude	34.052	33.931
Longitude	-118.257	-118.178
Vs30 [m/s] (Wills, 2006)	390	280
Z1.0 [km] (CVM-S4.26)	0.31	0.88
Z2.5 [km] (CVM-S4.26)	2.08	5.57
Simulation information		
CyberShake Run ID	831	830
Magnitude (Mw)	6 - 8.5	
# of ground motions	835,908	834,920
Simulation method	Hybrid broadband, splicing period 2s	

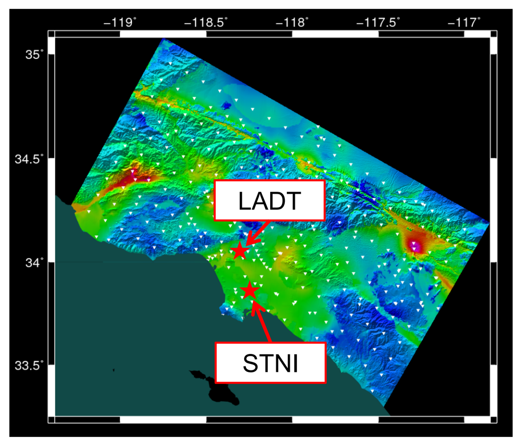

Figure 2. Location of considered CyberShake sites. Map modified from Graves et al. (2011).

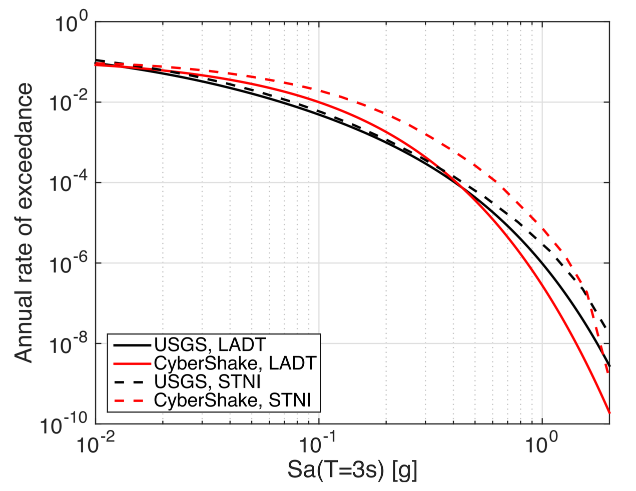

Figure 3. CyberShake and USGS hazard curves, T = 3s.

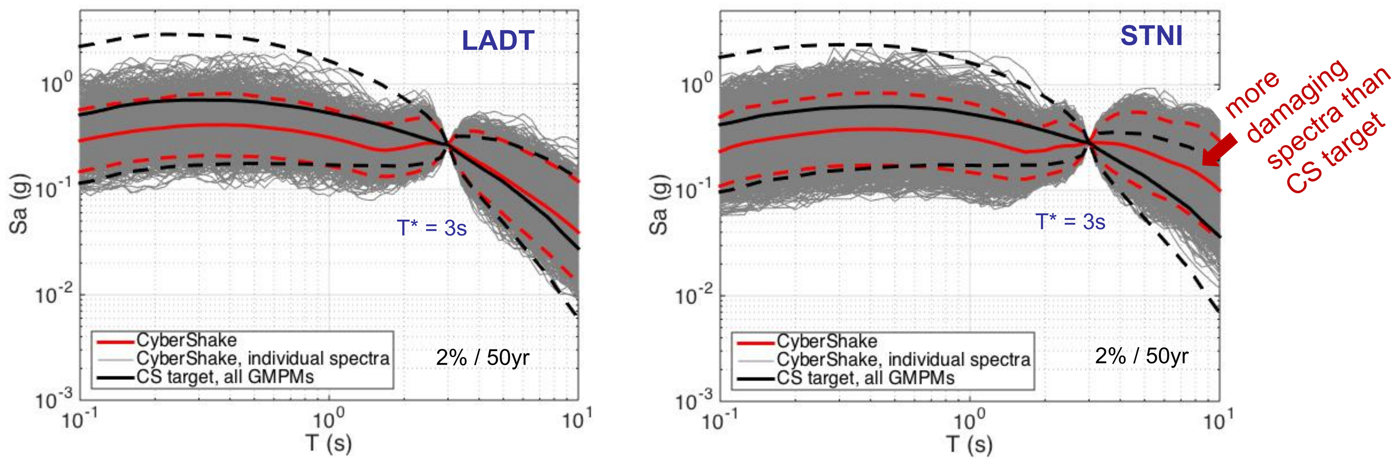

Figure 4. CyberShake-based and conventional conditional spectra (CS) at LADT and STNI sites.

Seismic demands are estimated using direct analysis (CyberShake) and multiple stripes analysis (NGA/USGS) with a conditional period of T* = 3s. Given a large number of available simulations, unscaled CyberShake seismograms were used in the direct analysis, while scaling was required for recorded motions.

LADT site:

- Similar long-period spectral shape of CyberShake-based and conventional CS targets result in similar collapse fragilities
- Probability of collapse in 50 years is about 25% higher for CyberShake, primarily due to differences in hazard curves
- Differences in exceedance rates of story drift ratios occur due to differences in hazard curves and more "peaked" mean spectral shapes of CyberShake motions as compared to conventional CS targets

STNI site:

- Difference between median collapse capacities is around 74%, resulting in roughly 20 times larger annual frequencies of collapse from CyberShake motions
- Differences in responses are primarily driven by large differences in spectral shapes between recorded and CyberShake motions

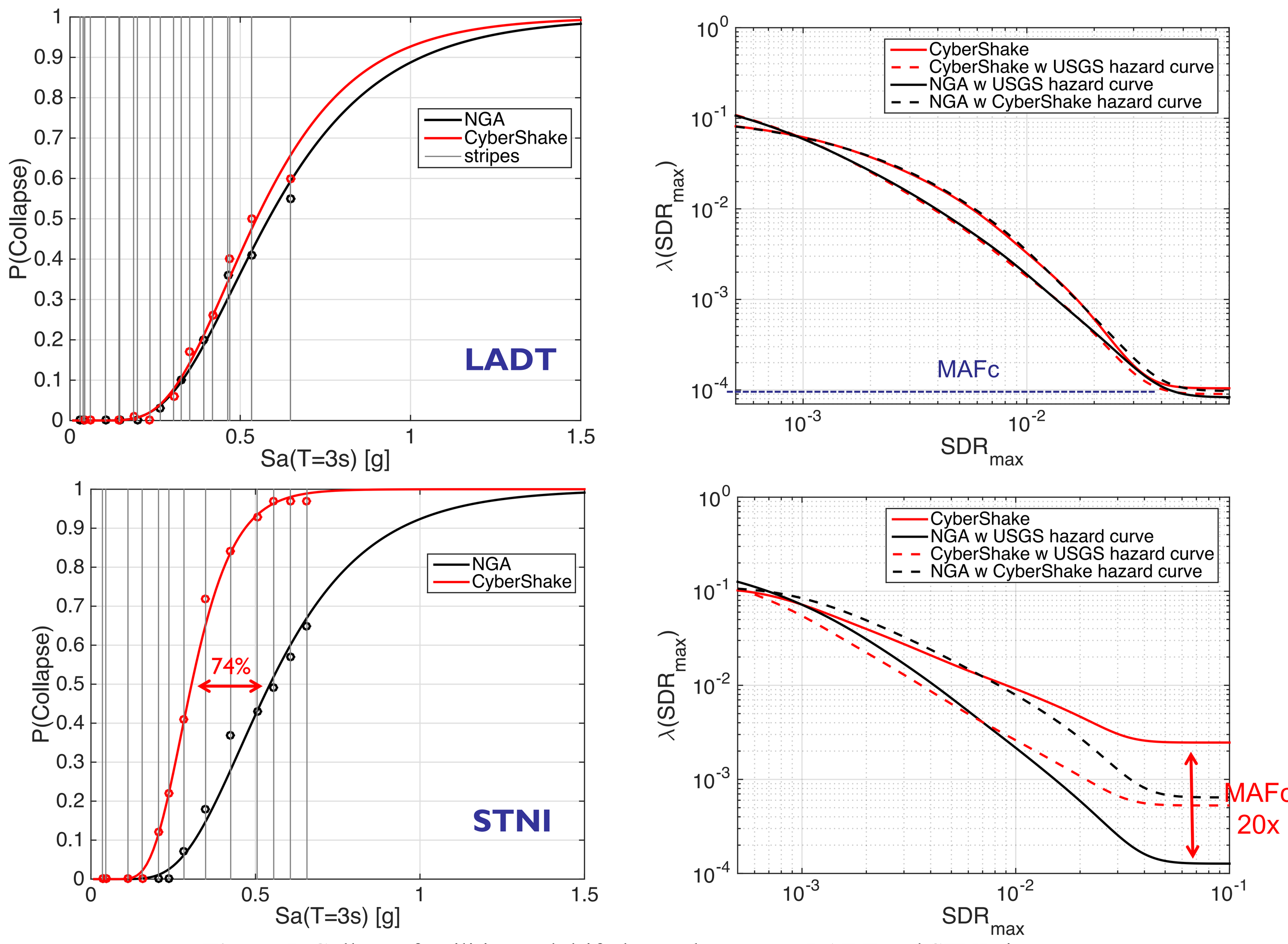

Figure 5. Collapse fragilities and drift demand curves at LADT and STNI sites.

4. Hazard and risk deaggregation

Performing the direct analysis using all of the CyberShake seismograms (~500,000 at each site) for the selected sites enables deaggregation of collapse risk and its comparison to seismic hazard (Fig. 6). This facilitates investigation of (1) earthquake sources contributing the most to collapse risk (Fig. 7) and (2) properties of ground motions contributing significantly to collapse risk (Fig. 8).

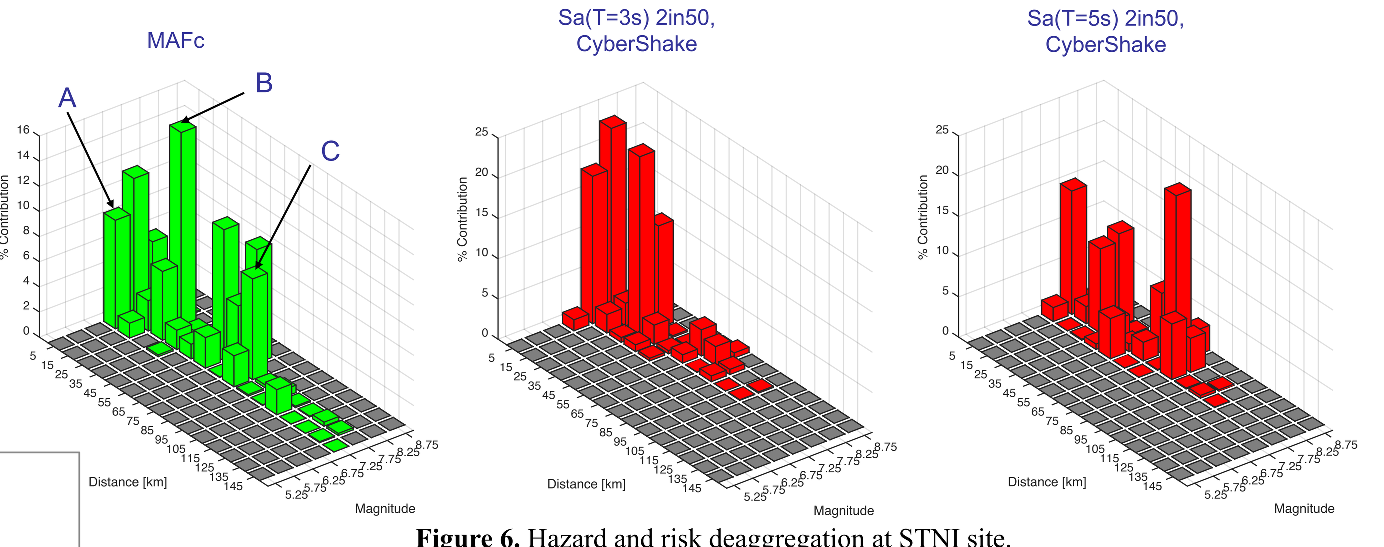

Figure 6. Hazard and risk deaggregation at STNI site.

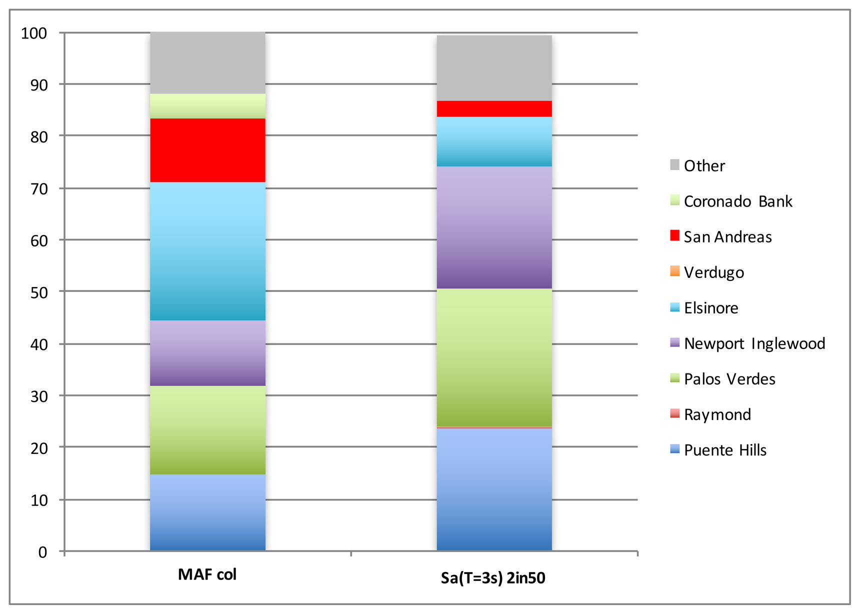

Figure 7. Contribution of sources to hazard/risk.

Properties of motions:

- Distinctly different spectral shapes and durations of ground motions from different deaggregation bins
- Differences in significant duration are reflected in spectral shapes of corresponding motions

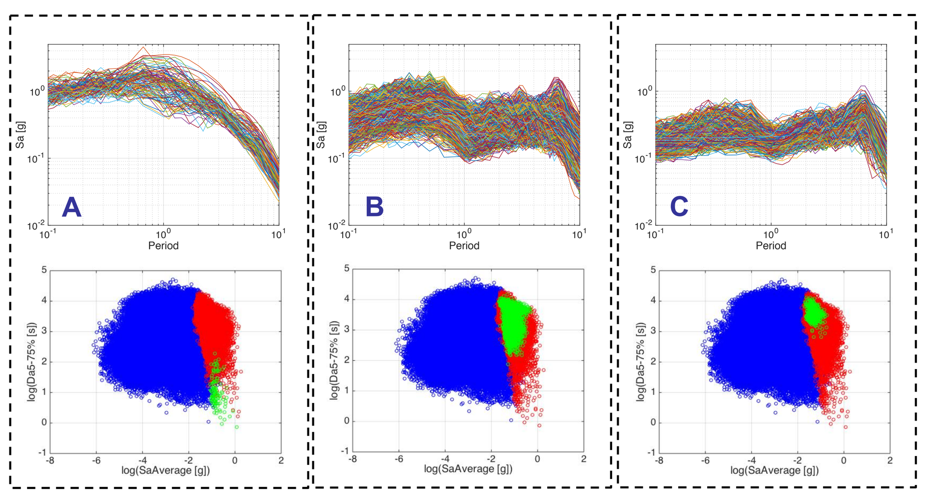

Figure 8. Properties of motions contributing to collapse risk.

5. Archetype long-period ground motions

Examination of the CyberShake seismograms causing collapse of the model building at the STNI site yields insights into waveform properties of the motions. In particular, seismograms are exhibiting long-period effects and can be grouped into following archetypes (Fig. 9) based on waveform similarity:

- Pulse-like motions
- Long-period cyclic (LPC) motions:
  - Single LPC component
  - Multiple LPC components
- Pulse-like & LPC combination
  - Distinct
  - Continuous

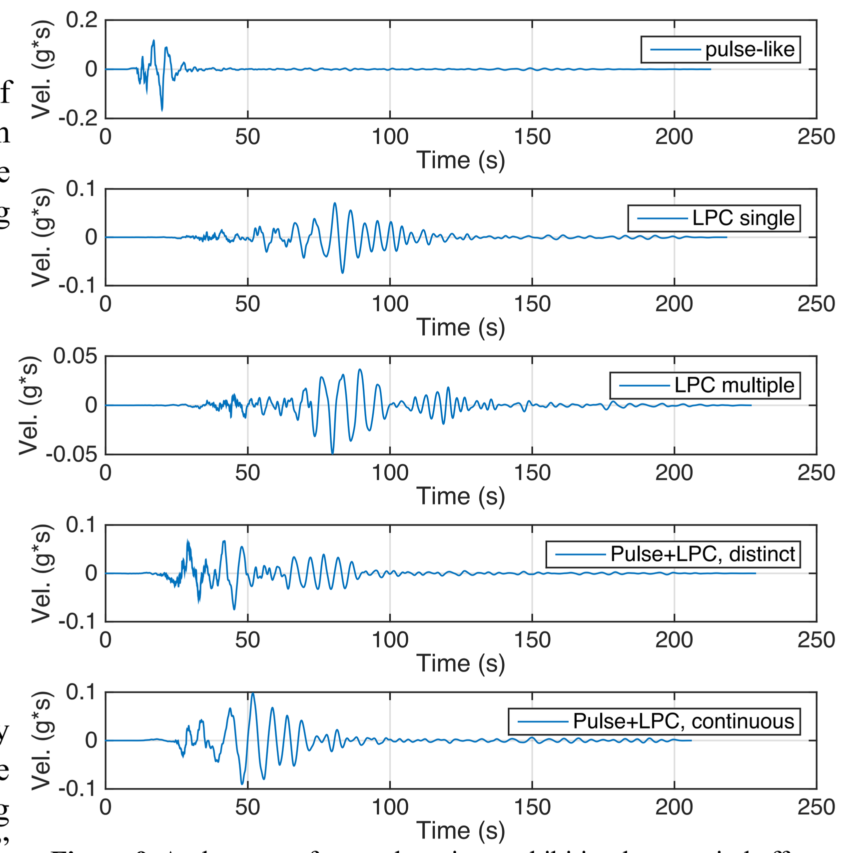

Figure 9. Archetypes of ground motions exhibiting long-period effects.

6. Basin vs. non-basin ground motion sets

To gauge the influence of long-period effects (presumably associated with the presence of sedimentary basin) on collapse response, incremental dynamic analysis is performed using spectrum- and duration-equivalent "basin" and "non-basin" ground motion sets. The set of basin motions were selected from CyberShake seismograms at the STNI site (basin site) to represent all archetype motions along with different magnitudes and distances. The set of non-basin motions were selected from CyberShake seismograms at the PAS site (rock site), which presumably do not contain any effects associated with the basin. Nominally equivalent ground motion sets (Fig. 10) cause significantly different collapse responses (Fig. 11), where basin motions are found to be more damaging than non-basin motions.

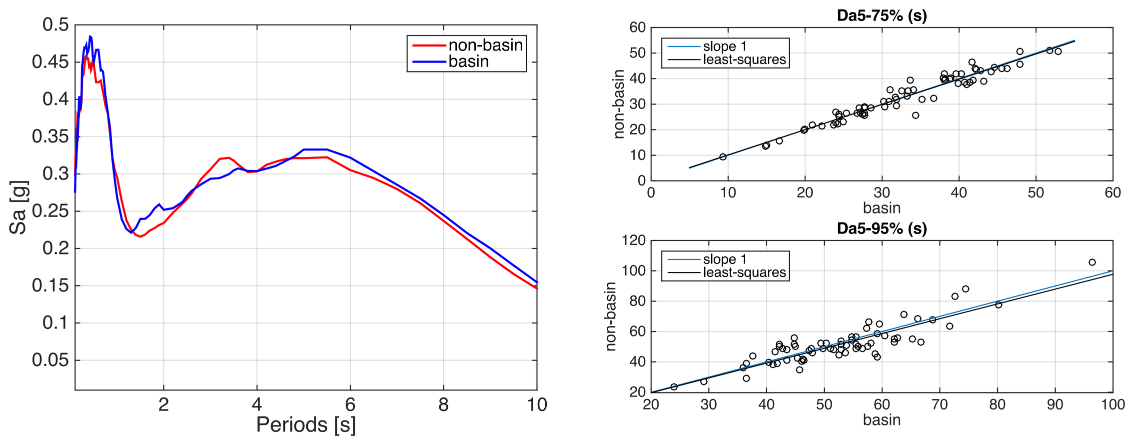

Figure 10. Basin vs. non-basin ground motion sets – ground motion selection.

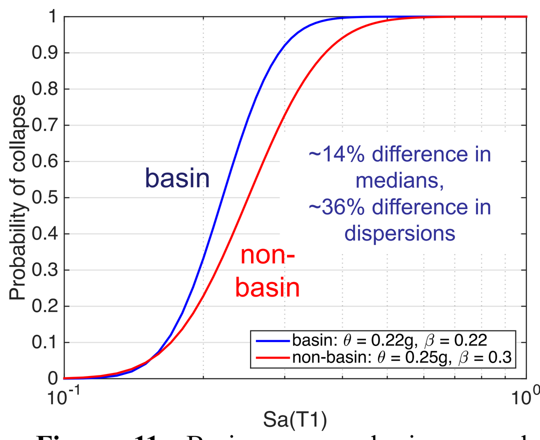

Figure 11. Basin vs. non-basin ground motion sets – collapse fragilities.

7. Novel intensity measures: duration & sustained amplitude adjusted (RSx) spectra and significant duration spectra

To further differentiate basin and non-basin ground motion sets that are equivalent in spectral shape and significant duration, we propose the following metrics: (1) duration and sustained amplitude adjusted response spectra, RSx spectra (Fig. 12) and (2) significant duration spectra (Fig. 13). These novel intensity measures help characterize damaging features of basin motions that contribute to collapse.

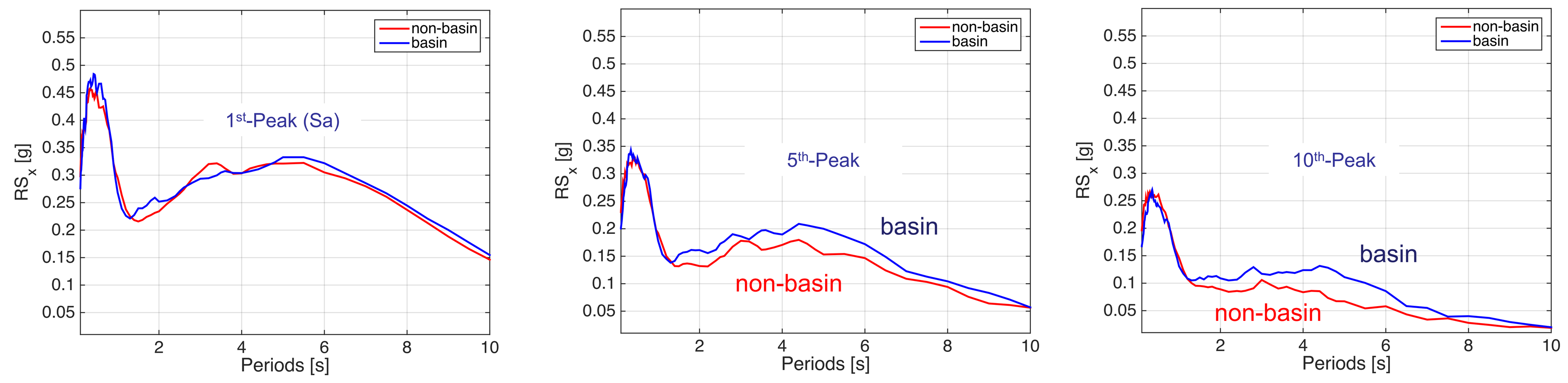

Figure 12. RSx spectra computed for the basin and non-basin ground motion sets.

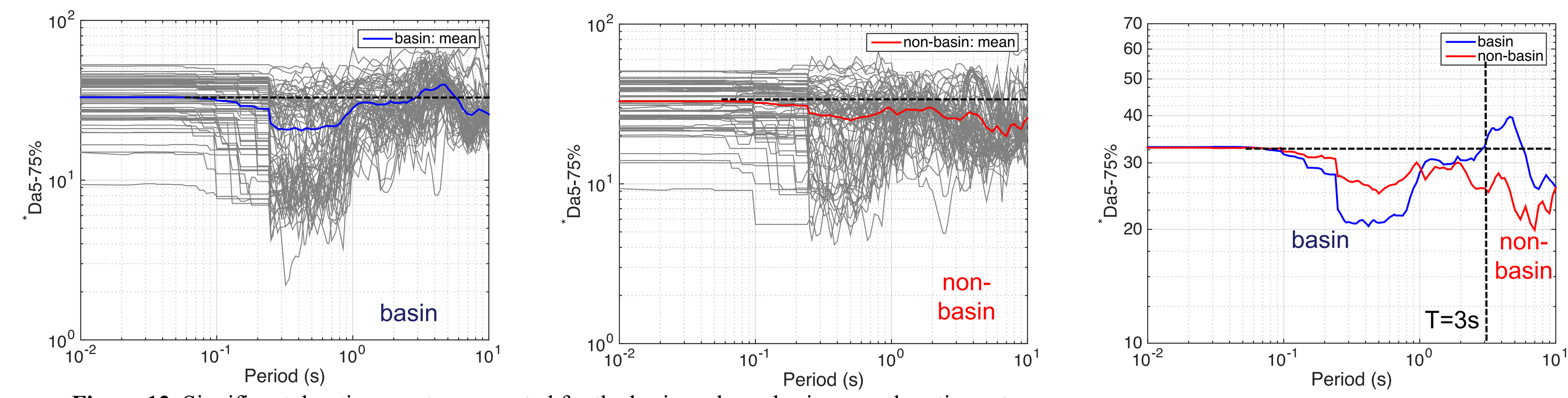

Figure 13. Significant duration spectra computed for the basin and non-basin ground motion sets.

- RSx spectra are computed from the x-th peak of SDOF response (similar to n-spectra proposed by Graf, 2009)
- Both metrics are useful for contrasting differences between otherwise equivalent sets

$$^*Da = \int a^2\,dt$$

From SDOF response

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