16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 2499
Registration Code: S-Z1463276748

SEISMIC RESPONSE OF A TALL BUILDING TO SIMULATED LONG-PERIOD GROUND MOTIONS

N. Bijelic [(1)], T. Lin [(2)], G.G. Deierlein[(3)]

[(1)] *Graduate Student Researcher, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305-3037, nbijelic@stanford.edu*
[(2)] *Assistant Professor, Dept. of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI 53201-1881, ting.lin@marquette.edu*
[(3)] *Professor, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305-3037, ggd@stanford.edu*

Abstract

Physics-based ground motion simulations are advancing to a state of enabling detailed characterization of extreme earthquakes, holding promise for providing novel insights to questions of engineering concern. For instance, presence of sedimentary basins is well recognized for potential detrimental effects on buildings, but their quantification has remained largely elusive due to limited availability of recorded motions. With a broader goal of exploring the areas where simulated earthquakes can offer unique engineering insight, this paper examines seismic performance of a 20-story building for two sites located in the Los Angeles basin. Comparative analysis of seismic hazard and demands is performed by: a) using “conventional” approaches relying on recorded motions coupled with probabilistic seismic hazard assessments from the U.S. Geological Survey; and b) by completely relying on physics-based simulations generated as part of the Southern California Earthquake Center CyberShake project. Site hazards are compared in terms of conditional spectra and significant durations; opportunities and challenges involved with estimation of intensity measure targets from simulations are discussed. In terms of seismic demands, the two approaches yield similar estimates for one site, while being drastically different for the other. Extent and sources of these discrepancies are investigated and opportunities for future work are discussed.

Keywords: tall buildings; physics-based ground motion simulations; probabilistic seismic hazard analysis; seismic risk; CyberShake

1. Introduction

One of the main challenges of making reliable risk assessments of tall buildings is limited data on strong earthquakes (~M8) and their effect on buildings. For example, whereas the collapse safety of tall buildings is likely to be influenced by large magnitude earthquakes with long durations and high long-period energy content, there are few available recorded ground motions to evaluate these issues. In the absence of recorded motions from past earthquakes, emergent physics-based ground motion simulations that incorporate fundamental fault rupture and site-specific characteristics provide an attractive alternative. Most pertinently, earth scientists associated with the Southern California Earthquake Center (SCEC) have developed extensive simulations of the Los Angeles Basin as part of the CyberShake project [1]. The main objective of the project is to perform probabilistic seismic hazard analysis (PSHA) by completely relying on numerical simulations of wave propagation. As a result, millions of site-specific seismograms are simulated, including very extreme ground motions, which offer opportunities for novel insights in areas of earthquake engineering concern that cannot be adequately addressed using limited database of recorded earthquakes.

The CyberShake ground motions used in this paper are classified as "hybrid-broadband" [2], which combine waveforms that are generated by physics-based earthquake rupture simulations with a high frequency stochastic component. The physics-based component of the simulations are well resolved for longer periods (currently for ~ T > 1s), but due to a combination of geophysical complexity and computational limitations, the physics-based approach does not capture well the high-frequency component of ground motions. Therefore, in order to obtain broadband ground motions, which are required for most engineering applications, the hybrid method combines the physics-based approach (sometimes referred to as the "deterministic" approach) at longer periods with a stochastic approach at higher frequencies. That is, low and high frequency seismograms are generated separately and then spliced together to form a broadband seismogram. The CyberShake ground motions used in this paper have components that are spliced together at periods of about T_{splice} = 2s.

An important step toward utilizing simulated ground motions in performance-based engineering is validation to demonstrate that simulated ground motions can reliably capture features that have a significant effect on structural response (see e.g. [3,4,5]). For instance, it was shown [6] that simulated motions can provide reliable estimates of seismic performance when used in the way in which recorded motions are conventionally used. This present work goes one step further with a broader goal of exploring the areas where simulated earthquakes can offer unique engineering insight.

To that end, this study focuses on comparative assessment of seismic performance of a 20-story building for two sites located within the Los Angeles basin. One site is located in the downtown areas of Los Angeles (LA), which is underlain by a soil layer about 2.1 km thick, and the second is a site where basin depth is much larger, about 5.6 km, which is presumed to be about the thickest region of the LA basin (values used here represent depths at which shear-wave velocities equal 2.5 km/s and are obtained from SCEC Community Velocity Models [7]). Comparative analysis of seismic hazard and demands is performed by: a) using a "conventional" approach relying on recorded ground motions coupled with probabilistic seismic hazard assessments based on empirically calibrated ground motion prediction models; and b) by completely relying on physics-based simulations generated as part of the SCEC CyberShake project for both hazard and ground motions. The "conventional" and CyberShake-based site hazards are compared in terms of conditional spectra and significant durations; some of the challenges involved with estimation of intensity measure targets from simulations are discussed. Thereafter, the seismic demands are compared in terms of collapse performance and peak story drift exceedance curves, and opportunities for future work are discussed.

2. Case study building an sites

2.1 Tall building model description

Tall building used in this study is an archetype model of 20-story reinforced concrete special moment frame that is representative of office buildings in California. The building was designed as part of a previous benchmark study [8], 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 [9] and the fundamental elastic period is estimated as T_1 = 2.6s. For additional details regarding design and modeling assumptions, see [8].

2.2 Site hazard – "conventional" vs. Cybershake

The study compares the building performance using (1) a conventional approach, relying on United States Geological Survey (USGS) data for hazard information and the Pacific Earthquake Engineering Center (PEER) Next Generation Attenuation (NGA) database [10] for recorded ground motions, and (2) a full simulation approach, where the site-specific hazard information and ground motions are obtained from the CyberShake simulations. The two LA basin sites chosen for this study from the CyberShake database are codenamed LADT and STNI (latitude/longitude: 34.052 / -118.257 and 33.931 / -118.178, respectively). The LADT site is located in Los Angeles down town and is of particular interest due to its societal importance. On the other hand, the STNI site is situated at the location where the basin depth is considered to be the largest; hence, the effects of basin structure on the resulting ground motions are very pronounced [1], particularly at long periods where ground motion prediction equations are relatively less well constrained.

Hazard at the two case study sites is expressed in terms of conditional spectrum (CS) targets (e.g. [11, 12]) which are commonly used for ground motion selection. The "conventional" hazard-consistent conditional spectra are computed based on the seismic hazard deaggregation information obtained from the USGS web tool [12, 13]. Given a complex geological setting in the L.A. basin, where multiple faults are significantly contributing to seismic hazard at a range of return periods, the "exact" CS targets are computed by considering the contributions of multiple causal earthquakes and ground-motion prediction models (GMPMs) following the approach of [12]. The GMPMs - consistent with PSHA - considered in the development of CS targets are BA08 [14], CB08 [15], and CY08 [16], as shown in Fig. 1 for LADT site. Given that hundreds of thousands of ground motions are simulated for PSHA purposes at each CyberShake site, the CS targets as implied by simulations can be computed from (unscaled) simulated motions that have the value of spectral acceleration at the conditioning period within the specified tolerance of the target spectral acceleration value. Individual spectra as well as the CS targets based on CyberShake motions that were within 1% tolerance of the target Sa value (from USGS) are also shown in Fig. 1.

An immediate observation from Fig. 1 is a noticeable "dent" in the mean values of CyberShake-based CS targets for periods close to the splicing period T_{splice} = 2s as used in the hybrid simulation method. This dent is noticeable in the CS targets for a range of return periods (although it gets less pronounced for smaller intensities) and is most probably an artefact of the splicing procedure used to generate broadband simulations (Note that the current update to the CyberShake simulations with a smaller splice period, T_{splice} = 1s, will provide further insight into this issue). A direct consequence of this is a large discrepancy in the mean values of the "conventional" and CyberShake-based CS targets for $T > T_{splice}$, as seen in Fig. 1a. Since the filtering employed in the splicing procedure reduces the spectral acceleration values of the low-frequency (deterministic) components of simulations at periods close to T_{splice}, using a conditioning period that is close to T_{splice} results in biased CyberShake-based CS targets (in essence, ground motions that correspond to larger intensities are used at lower intensities due to artificially reduced spectral accelerations). By comparison, when T = 3s is used as the conditioning period the "conventional" and CyberShake-based CS targets are in good agreement for periods larger than T_{splice} (Fig. 1b). For this reason, conditioning period T = 3s was used for ground motion selection and analyses presented in the following sections.

In addition to a good agreement in the means, the variability of CyberShake-based CS targets is also similar to their "conventional" counterparts for $T > T_{splice}$. However, for periods smaller than T_{splice}, i.e. for the stochastic component of the hybrid-broadband simulations, both the mean and variability of CyberShake ground motions are significantly smaller than predictions based on GMPMs (Fig. 1b). A smaller variability in the stochastic portion of hybrid motions was noticed in some previous studies (e.g. [17]) and presents an opportunity for improvement of the simulation methods. Although not shown in figures, such behavior was generally noticed for a large range of return periods. To avoid the bias in spectra at high frequencies, this study focuses on comparisons of engineering demand parameters (EDPs) that are primarily controlled by spectral content at periods longer than the fundamental mode of the case-study building. Examination of the extent and legitimacy of the bias at high frequencies is left for future studies.

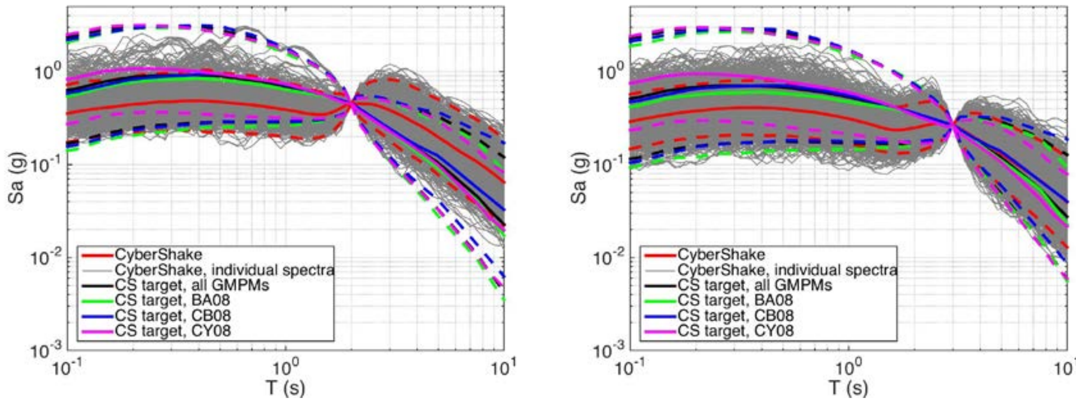

Fig. 1 – Comparison of conditional spectrum (CS) targets for LADT site based on USGS hazard and as implied by the CyberShake data, exceedance probability 2% in 50 years from USGS: a) conditioning period $T^* = 2$s; b) conditioning period $T^* = 3$s. CyberShake-based CS targets computed from unscaled simulated ground motions which have the value $Sa(T^*)$ within 1% tolerance (in units of g) of the target value. Ground motion prediction models considered: BA08 [14], CB08 [15], and CY08 [16].

Examination of the hazard at the STNI site reveals a much different situation in terms of long period spectral accelerations when compared to the LADT site. In particular, the mean Sa values in the long period range from the CyberShake-based CS targets are significantly larger compared to predictions from "conventional" CS targets, as shown in Fig. 2a. The CB08-specific CS target is closest to long-period CyberShake predictions, but in general the differences in mean predictions are large and were observed starting from very small return periods (e.g. 30 years). This would suggest a presence of significant basin effects on the ground motions at the STNI site and, assuming that the trends in CyberShake are valid, then it appears that the conventional GMPEs are not capturing the site–specific hazard for this site as well as they did for LADT.

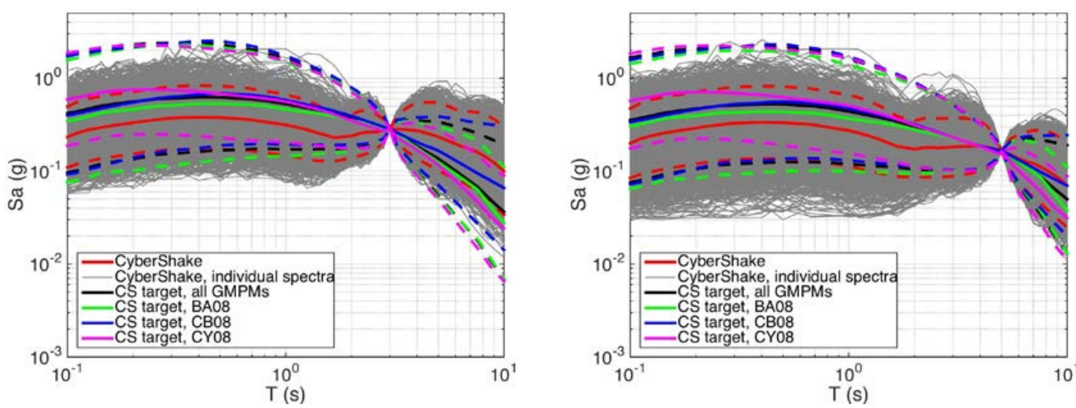

Fig. 2 – Comparison of conditional spectrum (CS) targets for STNI site based on USGS hazard and as implied by the CyberShake data, exceedance probability 2% in 50 years from USGS: a) conditioning period $T^* = 3$s; b) conditioning period $T^* = 5$s. CyberShake-based CS targets computed from unscaled simulated ground motions which have the value $Sa(T^*)$ within 1% tolerance (in units of g) of the target value. Ground motion prediction models considered: BA08 [14], CB08 [15], and CY08 [16].

The difference in the long-period means of CyberShake and "conventional" CS targets at STNI site is still evident when conditioning period is increased to $T^* = 5$s (Fig. 2b). Given that $T^* = 3$s is relatively far from T_{splice} (see [18]), it is unlikely that the differences in long-period means observed in Figure 2a are solely due to artefacts of the splicing procedure as was observed in the LADT case. Hence, for consistency with LADT analyses, the conditioning period $T^* = 3$s was used for ground motion selection and analyses at the STNI site as well. Shown in Fig. 3 are comparisons of hazard curves for the two sites for $T = 3$s. However, the extent to which the splicing procedure affects the long-period accelerations and its implications warrant further study.

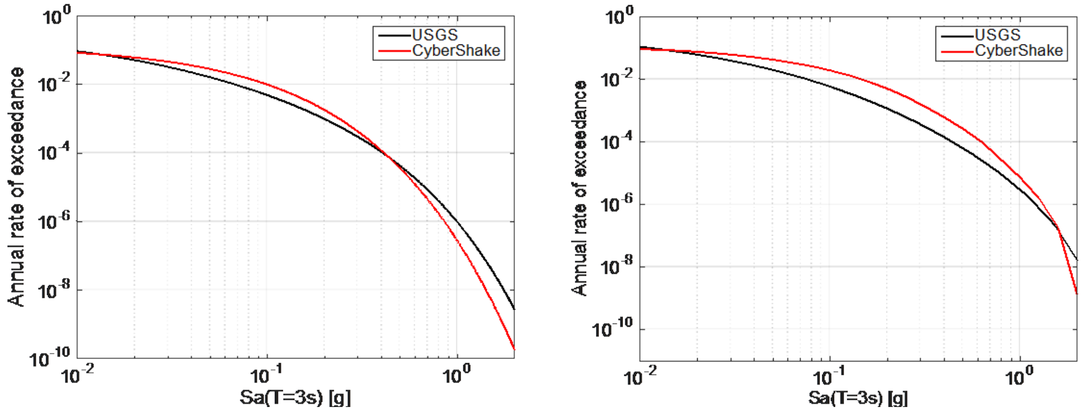

Fig. 3 – Comparison between “conventional” (i.e. USGS) and CyberShake-based hazard curves for period T = 3s: a) LADT site; b) STNI site.

As an aside, it is mentioned that the “dent” in the mean CyberShake-based CS around T_{splice}, as well as comparatively smaller means and variability in the stochastic portion of the spectra are also observed at the STNI site. However, by comparing the mean Sa values in Fig. 2a, a relatively smooth transition between the long-period ($T > T^*$) CyberShake and shorter period “conventional” CS targets can be seen. This suggests an opportunity for combining the empirical hazard predictions with physics-based simulations for PSHA purposes, utilizing each approach in areas where it is better constrained or theoretically resolved.

In addition to comparisons of spectra, ground motion durations were also compared at the two sites. Significant durations based on Arias intensity and energy integral (indicated as Da and Dv, respectively) are used in this work (for definitions see e.g. [19]). Conditional distributions of Da were obtained by extension of the “exact” CS approach [13] to durations. The duration model KS06 [19] was used along with correlation relations between spectral accelerations and durations by [20]. A general observation is that the significant durations, both $Da_{5\text{-}75\%}$ and $Da_{5\text{-}95\%}$, obtained from CyberShake motions are significantly larger than the durations predicted by the hazard-consistent conditional distributions. This was noticed at both LADT and STNI sites, and for all considered intensities. For instance, for the return period of 475 years at the LADT site, median duration from CyberShake is about two times longer compared to conditional distribution targets (Fig. 4a).

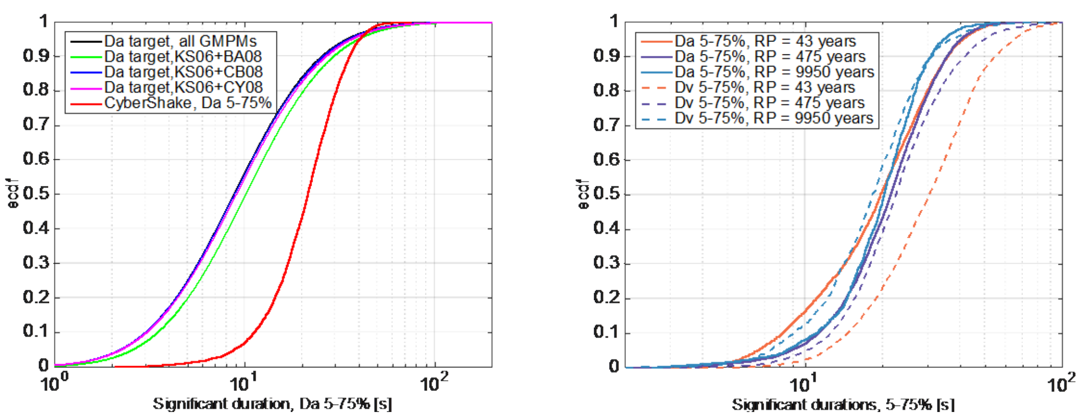

Fig. 4 – Significant durations of ground motions at the LADT site: a) comparison of conditional duration targets and CyberShake data, return period 475 years, T = 3s; b) comparison of Da and Dv durations from CyberShake data at return periods of 43, 475, and 9950 years.

Since the Da is calculated from acceleration seismograms, its value is more sensitive to higher frequency content than the value of Dv which is based on velocity. Given the stochastic nature of higher-frequency components of CyberShake motions, the large observed discrepancy in DS may in part be an artefact of the hybrid simulation procedure. For example, if the durations of the high frequency portions are not properly represented such that the durations of the entire signal are dominated by longer period components, the values of duration calculated as Da would be more representative of the values of Dv. In that case, a part of discrepancy observed in Fig. 4a may be due to this effect since the duration models predict longer durations for Dv than for Da, and the more appropriate comparison to make in Fig. 4a would be between Dv values. To investigate this, a comparison is made between Da and Dv values (5-75%) calculated from CyberShake for return periods of 43, 475 and 9950 years. As shown in Fig. 4b, at the lowest return period, the difference between Da and Dv values is quite pronounced. However, with increasing intensity this difference reduces such that Da and Dv values become very similar, as seen for instance for the 475 return period values. This suggests that higher frequency portions do not contribute much to duration, and hence, the Da values are actually more representative of the Dv, potentially raising some doubts on the validity of CyberShake predictions. On the flip side, the fact that Da and Dv values are becoming more similar with increasing intensity may be representative of long-period effects in ground motions which get more pronounced for larger events. This in turn gets picked up in CyberShake simulations, while GMPEs are not sensitive to this site-specific effect. Investigation of this issue merits further study, but is beyond the scope of this paper. Similar observations for duration were made for the STNI site. Additionally, for same return periods, the durations of CyberShake motions at the STNI site are longer compared to the LADT site; this is expected given a significantly greater basin depth at the STNI site.

3. Comparison of seismic demands – conventional vs. CyberShake

Seismic demands of the archetype tall building, in particular collapse fragilities and drift exceedance curves, are estimated at the LADT and STNI sites by performing a multiple stripe analysis. Hazard-consistent CS and conditional duration ($Da_{5\text{-}75\%}$) targets, as described in the previous section, were used to select sets of recorded and simulated motions as inputs for response history analysis; at each stripe, sets of 100 motions are selected. In the “conventional” approach, recorded ground motions from the PEER NGA database are selected and scaled to match the “exact” hazard targets based on all GMPMs (weights of 0.8 and 0.2 were used for CS and $Da_{5\text{-}75\%}$, respectively). For the CyberShake part, a subset of all available motions that were used in the development of the CyberShake-based hazard targets are selected, ensuring that the CS and Da targets are properly represented. Given a large availability of simulated motions at a range of intensities, no scaling was used in the selection of CyberShake motions.

Estimates of seismic demands at the LADT site are shown in Fig. 5. Given the similarity of the long-period spectral shapes of “conventional” and CyberShake-based CS targets (Fig. 1b), close agreement in the obtained fragility curves is not unexpected. When integrated with corresponding hazard curves (Fig. 3a), the estimate of probability of collapse in 50 years is about 25% higher for CyberShake compared to NGA (0.51% compared to 0.41%). CyberShake also causes comparatively higher exceedance rates of the maximum peak story drift ratio (SDR_{max}), as shown in Fig. 5b. For instance, SDR_{max} of 1% is exceeded about 1.7 times more frequently; such differences are expected given the differences in hazard curves.

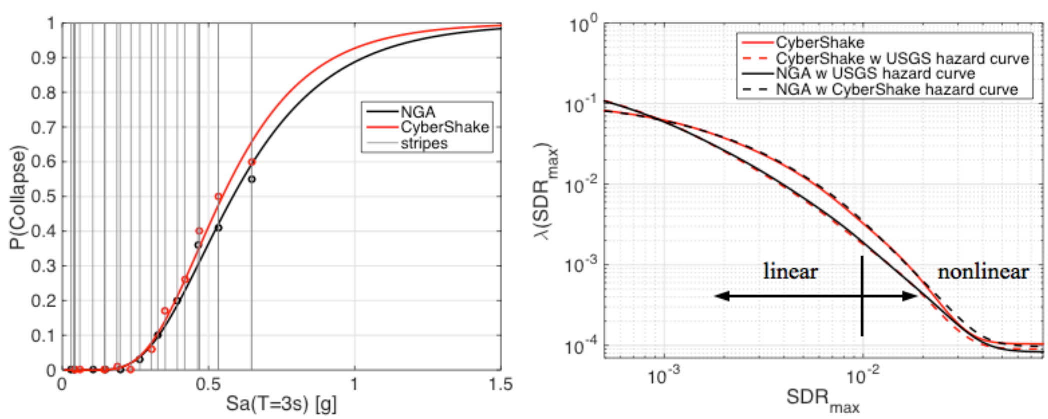

Fig. 5 – Seismic demands at the LADT site: a) collapse fragility curves; b) drift exceedance curves for peak maximal story drift ratio (SDR_{max}).

To examine the extent to which the differences in results can be attributed to differences in hazard curves, the drift exceedance curves were recomputed by using CyberShake motions with the USGS hazard curve as well as by combining the NGA motions with the CyberShake hazard curve. As shown in Fig. 5b, exceedances of drifts associated with linear structural response are primarily controlled by the hazard curves. On the other hand, differences in the nonlinear region are not fully explained by hazard curves and are traced back to differences in spectral shape. As noted in the previous section, for periods smaller than T_{splice}, i.e. for the stochastic component of the hybrid-broadband simulations, both the mean and variability of CyberShake ground motions are significantly smaller than predictions based on GMPMs (Fig. 1b). Since this difference increases with the return period, it effectively results in more "peaked" mean spectral shapes of CyberShake motions when compared to "conventional" CS targets. This explains higher exceedance rates when NGA motions are combined with CyberShake hazard, and lower exceedances when CyberShake motions are coupled with the USGS hazard.

Although there are differences in response estimates from the "conventional" and CyberShake-based approaches, the extent of the differences observed at the LADT site is not too large. This is potentially good news for structures located in that region and a reassuring example of agreement between engineering approaches based on empirically calibrated inputs and state of the art physics-based simulations. At the STNI site, however, the "conventional" and CyberShake-based approaches yield drastically different results, as seen in Fig. 6. For instance, the difference between median collapse capacities is around 74%, which results in roughly 20 times larger annual frequencies of collapse from CyberShake motions compared to these from the "conventional" approach. Given the large differences in spectral shapes of ground motions (Fig. 2a) as well as hazard curves (Fig. 3b) these results are not unexpected. However, whether the obtained estimates are reasonable or not is a focus of ongoing investigation. In any case, further studies offer potential for fruitful contributions both in terms of feedback to ground motions simulators on areas where simulations can be improved as well as for tackling of some fundamental earthquake engineering questions that cannot be adequately addressed using a limited database of recorded ground motions.

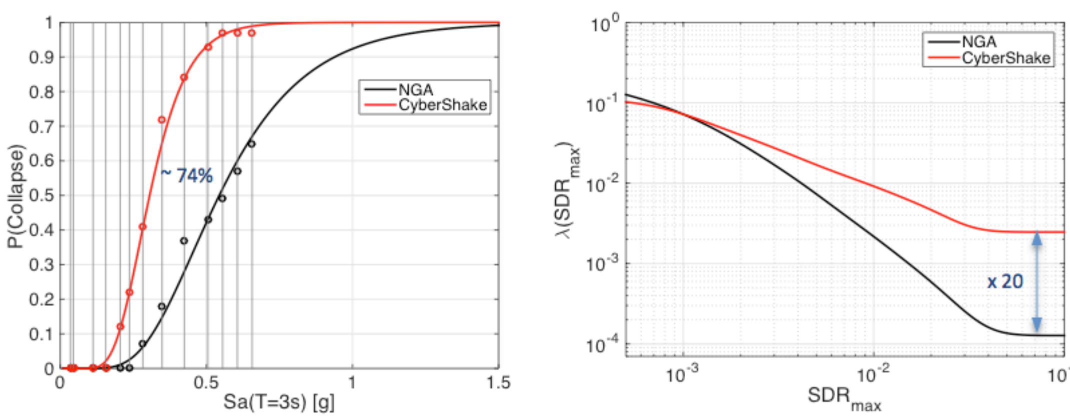

Fig. 6 – Seismic demands at the STNI site: a) collapse fragility curves; b) drift exceedance curves for peak maximal story drift ratio (SDR_{max}).

4. Conclusions

This paper examined the seismic performance of a 20-story building for two sites located in the Los Angeles area. The first site is located in L.A. downtown, where most of the tall buildings are situated; the second site was selected at a location where basin depth is presumed to be the largest. Seismic hazards and demands obtained using "conventional" approaches, i.e. utilizing the output of GMPM-based PSHA for hazard coupled with appropriate recorded motions for nonlinear response-history analyses, were contrasted to results obtained by completely relying on site-specific, physics-based simulated hazard and ground motions. The two approaches yielded very similar estimates for the L.A. downtown site, but were drastically different for the other location. In particular, the estimate of mean annual frequency of collapse based on simulations at the deep-basin site was roughly 20 times larger compared to the "conventional" estimate.

Physics-based earthquake simulations hold the promise of dramatically improving characterization of strong ground motions by representing the effects of geologic features that are currently accounted for empirically by conventional GMPMs. Large variabilities that have heretofore been attributed to inherent randomness, may be constrained by wave propagation that accounts explicitly for local geologic terrain. Simulation of large magnitude earthquakes will also fill a gap in existing ground motion databases. The study described in this paper is part of a larger effort by the engineering and earth science research community to validate simulations and to explore areas where ground motion simulations can provide unique insight to earthquake engineering challenges that cannot be adequately addressed using limited data on recorded strong earthquakes. Ground motion simulation is still a rapidly evolving field, so the analyses presented here are by no means complete or comprehensive. Rather, they are a step towards exploring the future promise of simulations and helping to identify and direct efforts to improve ground motions simulations and make them useful for engineering applications.

4. Acknowledgements

This research is supported by the Fulbright S&T Program, the John A. Blume Earthquake Engineering Center, the Shah Family Fellowship and the Southern California Earthquake Center (SCEC projects #13161, 14228, 15113). The authors gratefully acknowledge researchers associated with SCEC for developing and advancing ground motion simulations. In particular, we thank Robert Graves, Phil Maechling, Scott Callaghan and Kevin Milner for their support and help with CyberShake simulations. We thank the PEER Center for providing the NGA database. Analyses presented herein were performed using the Sherlock computing cluster at Stanford University.

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