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

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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, $T_2 = 0.9$ sec

### 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

Ref: PEER TBI (2011).
San Francisco Downtown, SFDT (8029-RIN)  
[1728 BBP Records]

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

Major seismic sources for SFDT site
Intensity Measures (IMs)

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

Ground motion selection

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

Ref:

[4]: Afshari & Stewart (2016).
[5]: Bradley (2010).
[7]: Bijelic, Lin, & Deierlein.
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.
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
Multi-Stripe Analysis (MSA)

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![Graphs showing Maximum Story Drift Ratio and Peak Floor Acceleration](image-url)
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

Collapse Fragilities

Stripe Analysis - Story Drift Ratios

Seismic hazard curve
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.

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

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

Sa,average & SaRatio

- **Sa,avg**: average PSA values over a period range
- **SaRatio**: the ratio between Sa(T₁) 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 ($SDR_{\text{max}}$)**
  Comparable up to 2%/50yr
  <10% difference under 2%/200yr

- **Peak Floor Acceleration (PFA)**
  Comparable up to 2%/50yr
  <10% difference under 2%/200yr
ASCE 7-16 Procedure

Ground motion selection

- **Site information:**
  - Site class: B
  - $S_s = 1.5 \text{ g}$
  - $S_1 = 0.6 \text{ g}$
- **Target:** ASCE 7-16 MCE$_R$/DBE spectrum
- **Record number:** 11
- **Criteria:**
  - Consistent $M$, $R$, and mechanism
  - Close site condition
  - Mean $S_a \geq$ target over $(0.2T_1 \sim 1.5 \cdot T_1)$

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

$M = 7.79$
$R = 14.4 \text{ km}$

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

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**
**MCE<sub>R</sub> (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.

![Graph showing time history response acceleration (T<sub>cond</sub> = 5 sec) and higher modes (T<sub>2</sub> ~ 1.0 sec)]
Summary (San Francisco Site)

1. Simulated (BBP) motions can be selected/scaled to match the PSHA target IMs (CS+D_{55-75}) 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)

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

MCEr (T=5s):
EP: 18%
SSA: 21%
Others: 61%

Major seismic sources for LADT site

San Andreas ~M7.9 (SSA)
Elysian Park ~M6.6 (EP)
Others ~M7.2
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)

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

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

Ground motion selection ($T_{\text{cond}} = 3\text{ s}$, 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

Ground motion selection ($T_{\text{cond}} = 3$ 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, $T_{\text{cond}} = 3$ 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**
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**
  - Target median \( D_s \approx 31 \text{ sec} \)
  - \( Sa(3s) = 0.39g \)
  - \( \Delta \): Target median \( D_s \) = 31 sec

- **Elysian Park**
  - Target median \( SaRatio = 1.6 \)

**NGA**
- 8 collapses
- \( Sa(3s) = 0.39g \)
- \( \Delta \): NGA collapse

**BBP**
- 0 collapses
- \( \Delta \): BBP collapse

**Collapse cases plotted vs. GM Spectral Shape & Duration**

- Large SaRatio
- Small SaRatio

**LADT - South San Andreas**
- 2in200 - 7 GMs
- \( Sa(3s) = 0.39g \)
- NGA non-collapse
- BBP non-collapse
- NGA collapse
- BBP collapse

**LADT - Elysian Park**
- 2in200 - 29 GMs
- \( Sa(3s) = 0.39g \)
- NGA non-collapse
- BBP non-collapse
- NGA collapse
- BBP collapse
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

Selected records vs. target spectrum (2%/200yr, CB2008).
Seismic hazard deaggregation: $\text{Sa} = 0.3925 \text{ g}$, $R = 4.03 \text{ km}$, $M = 6.60$, 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 Atkinson
Reselect records by 4 schemes to BSSA 2014 target

NGA records
- \( M: 6\sim8, R: 0\sim175 \text{ km} \)
- \( V_{s30}: 198\sim629 \text{ m/s} \)
- 14 reverse-fault records
  (2 Northridge records)
  - Maximum scaling: 29

NGA (causal limits)
- \( M: 6\sim7, R: 0 \sim 10 \text{ km} \)
- \( V_{s30}: 195 \sim 585 \text{ m/s} \)
- 29 reverse-fault records
  (11 Northridge records)
  - Maximum scaling: 23

NGA (causal & scaling limits)
- \( M: 6\sim7, R: 0 \sim 10 \text{ km} \)
- \( V_{s30}: 195 \sim 585 \text{ m/s} \)
- 29 reverse-fault records
  (17 Northridge records)
  - Maximum scaling: 5

BBP records
- \( M = 6.60, R \sim 4.03 \text{ km} \)
- \( V_{s30} \sim 390 \text{ m/s} \)
- Maximum scaling: 5

Comparison of selected records (\( T_{\text{cond}} = 3 \text{ sec} \)) 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

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: 23

BBP records
- $M = 6.60$, $R \sim 4.03$ km
- $Vs30 \sim 390$ m/s
- Maximum scaling: 5

Comparison of building collapses ($T_{\text{cond}} = 3$ 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
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)

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)
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 ($CS + D_{75}$) 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

3D Simulations
- Velocity Profile (SCEC CVM-S 4.26)
- Wave Propagation

Physics Based & Stochastic (BB)
- Physics Based $T > 1$ second
- Splicing period $\sim 1$ second

PSHA Approach
- Multiple ruptures following UCERF 2
- Faults within 200 km

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
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)

Hazard Curves

Conditioning Period: T* = 3s
(20 story building, T1 = 2.6s)

Significant Duration, Ds (s)
Direct Simulation with CyberShake

Structural Response Comparisons

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

20-story building, $T_1 = 2.60s$
Direct Simulation with 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, $T_1 = 2.60s$
Direct Simulation with CyberShake

Deep Basin Site
LADT: \( V_{s30} = 390 \text{ m/s}; Z_{1.0} = 0.3 \text{ km} \)
STNI: \( V_{s30} = 280 \text{ m/s}; Z_{1.0} = 0.9 \text{ km} \)

\[ T^* = 3s \]

\[ 2\% / 50yr \]

more damaging spectra than CS target
Direct Simulation with CyberShake

**LADT**

- **Period (s)**: $10^{-1}$ to $10^1$
- **Sa(g)**: $10^{-3}$ to $10^0$
- **Annual rate of exceedance**: $10^{-6}$ to $10^{-1}$
- **STNI**: $2\% / 50\text{yr}$

**STNI**

- **Period (s)**: $10^{-1}$ to $10^1$
- **Sa(g)**: $10^{-3}$ to $10^0$
- **Annual rate of exceedance**: $10^{-6}$ to $10^{-1}$
- **STNI Duration**: $2\% / 50\text{yr}$

**LADT Hazard**

- **CDF**: $0.0$ to $1.0$
- **Da target, all GMPEs**
- **CyberShake, Da S-75%**

**STNI Hazard**

- **CDF**: $0.0$ to $1.0$
- **Da target, all GMPEs**
- **CyberShake, Da S-75%**

**Duration**

- **Da5-75% (s)**: $10^0$ to $10^2$
CyberShake: LA downtown vs STNI sites

20-story building, $T_1 = 2.60$ s

Collapse Fragility

STNI

Story Drift Exceedence

MAFc 10x
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

San Andreas
Raymond
Puente Hills

- MAF col
- PSDR 2in50
- Sa(T=3s) 2in50

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