Structural Reliability of Buildings Subjected to Simulated Ground Motions using a Novel Probabilistic Approach

J. Ramon Gaxiola-Camacho
Associate Professor, Dept. of Civil Engineering, Autonomous University of Sinaloa, Culiacan, Mexico

Dante Tolentino
Associate Professor, Departamento de Materiales, Universidad Autónoma Metropolitana, Mexico City, Mexico

Federico Valenzuela-Beltran
Associate Professor, Dept. of Civil Engineering, Autonomous University of Sinaloa, Culiacan, Mexico

Aaron Gutierrez-Lopez
PhD Student, Dept. of Civil Engineering, Autonomous University of Sinaloa, Culiacan, Mexico

ABSTRACT: The catastrophic power of earthquakes has been reported in numerous documents. For example, the occurrence of certain ground motions as the 1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe, represented economic losses of about 4, 6, 30, and 200 billion dollars, respectively. During the shaking of the above-mentioned and several other earthquakes, an inadequate structural performance has been observed in Steel Moment Resisting Frames (SMRFs). In most of the cases, SMRFs are designed using simplified methods of analysis which are permitted by certain building codes. However, to extract as accurate as possible the structural response of SMRFs subjected to ground motions, the nonlinear behavior of them must be properly extracted, generally using time history analysis. Unfortunately, for certain locations, the main problem is related to the availability of ground motions records. In this sense, an option that is becoming very popular is the use of simulated ground motions. Nevertheless, the use of simulated ground motions in time history analysis is still a research topic under development. The knowledge gap is mainly associated to the lack of approaches to artificially generate ground motions and their proper validation for specific applications as the earthquake-resistant design of SMRFs. Based on the above discussion, an approach that integrates the finite element method, response surface method, and first order reliability analysis is developed to calculate the structural reliability of SMRFs excited by synthetic ground motions generated via the Broadband Platform (BBP). Such a software represents an open-access platform developed by the Southern California Earthquake Center. In this context, the validation of the BBP is performed with the help of a 2-story SMRF excited using real and simulated versions of the 1994 Northridge earthquake. Then, a comparison is presented in terms of response spectrum and structural reliability. Once BBP is properly verified, an adequate set of ground motions is generated for a specific zone in the Los Angeles area. Using such a set of ground motions, 11 of them are properly selected considering a target response spectrum and dynamic properties of a 3-story SMRF. Hence, reliability is calculated for the 3-story SMRF in terms of reliability index and probability of failure.

1. INTRODUCTION

Designing a structure using multiple time histories, as suggested in recent design guidelines, is a step in the right direction. Based on previous studies about the performance of structures under the action of earthquakes, it has been documented the necessity of simulated ground motions in areas where finding real records is a challenge. When the availability of ground motions is not sufficient for nonlinear analyses, the ASCE (American Society of Civil Engineers) building code (ASCE 7-16, 2016) recommends the use of "appropriate simulated ground motions". Unfortunately, no further guidance is reported for the simulation of them. The main problem is how to generate such ground motions representing the seismic hazard of the zone. Several investigations reported in the literature propose how to generate ground motions using appropriate simulation techniques (Burks *et al.*, 2015; Cacciola & Zentner, 2012; Yamamoto & Baker, 2013; Shields, 2015). Within this context, a Broadband Platform (BBP) developed by the Southern California Earthquake Center (SCEC) is used in this paper for the artificial generation of time histories (SCEC, 2016). Then, the structural risk is of Steel Moment Resisting Frames (SMRFs) is calculated using simulated ground motions implementing a novel probabilistic approach which integrates the finite element method, response surface method, and first order reliability method. In addition, Validation of the BBP is performed with the help of a 2-story steel frame, it is excited using real and simulated versions of the 1994 Northridge earthquake. A comparison is made in terms of response spectrum and structural reliability. Once BBP is properly verified, an adequate set of ground motions is generated for a specific zone in the Los Angeles area. Using such a set of ground motions, 11 of them are properly selected considering a target response spectrum and dynamic properties of a 3-story steel frame. Then, reliability is calculated for the 3-story steel frame which was designed for the location under consideration. Based on the results of this paper, the application of the novel probabilistic approach considering simulated ground motions is demonstrated.

2. THE SCEC BROADBAND PLATFORM

The BBP is an open-source software developed by the SCEC for hybrid broadband simulation of ground motions (SCEC, 2016). Several researchers have developed modules of the BBP for nonlinear site effects, low and high frequency seismogram synthesis, and rupture generation (Graves & Pitarka, 2010; Schmedes *et al.*, 2010; Mai *et al.*, 2010). To simulate ground motions using the BBP, a single-plane fault surface should be described. A simple description of the rupture is defined by the user in terms of hypocenter location, magnitude, rupture dimensions, dip, strike, and rake. This information is used by the BBP rupture generator module and a detailed time history of slip on the rupture surface is created. A list of stations where ground motion time histories will be simulated is also provided by the user in terms of latitude, longitude, and V_{S30} (shear wave velocity of the top 30 m of the subsurface profile) of the specific site. Both low- and high-frequency synthesis modules compute deterministically and stochastically frequency seismograms, respectively. Such seismograms are then merged at a frequency of approximately 1 Hz. Furthermore, an empirical site amplification is applied to its Fourier spectrum depending on the corresponding target value of V_{S30}. At the end, results are reported for every station in terms of three acceleration time histories: North-South (N-S), East-West (E-W), and Vertical (V). The BBP sequential process is illustrated in Figure 1.

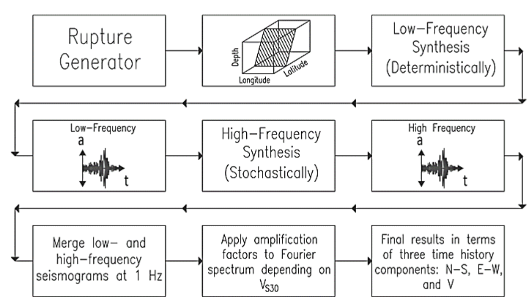

Figure 1: Flowchart of the BBP process.

3. RUPTURE GENERATION, LOW- AND HIGH-FREQUENCY SEISMOGRAMS, AND SPECIFIC AMPLIFICATION FACTORS

A description of the physical characteristics of the rupture is a fundamental element of the BBP. To properly generate the rupture, the required parameters are hypocenter (rupture initiation point), fault location (latitude and longitude), geometry (width, length, dip, and strike), rake (slip direction), and magnitude. Figure 2 illustrates the BBP rupture characterization.

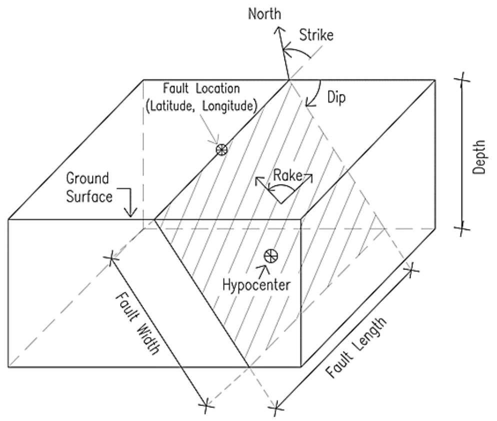

Figure 2: Illustration of rupture.

As previously mentioned, the BBP process begins computing individually the low- and high-frequency ranges, and then both are combined to produce a time history. When frequencies are smaller than 1 Hz, the approach is deterministic, containing a theoretical representation of wave propagation and fault rupture, trying to replicate recorded ground-motion amplitudes and waveforms (Graves & Pitarka, 2010). When frequencies are greater than 1 Hz, the BBP uses a stochastic representation in terms of source radiation, combining scattering effects and a simplified theoretical representation of wave propagation. Since wave propagation effects and source radiation are mainly stochastic at frequencies equal to or higher than 1 Hz, different simulation approaches for different frequency bands are used. This demonstrates the absence of information about higher frequencies of ground motions. At the final stage of the BBP process, nonlinear amplification factors are applied to the simulated time histories. They incorporate site-specific geologic conditions in the final seismograms. Nonlinear amplification factors are based on the V_{S30} of the site of interest (Walling *et al.*, 2008). In this paper, the BBP version v16.5.0 (SCEC, 2016) is used for ground motion simulations. As previously discussed, several methods are available in the BBP for the simulation of ground motions. Among them, the method proposed by Graves & Pitarka (2010), hereafter denoted as GP method, is utilized for the simulations as discussed in the next sections.

4. NOVEL PROBABILISTIC APPROACH

Up to this point of the paper, the process behind the simulation of ground motions using the BBP has been documented. Hence, the novel probabilistic approach is presented in this section of the paper. In the proposed algorithm, the necessary response information of structures subjected to simulated ground motions is generated at several sampling points by calculating the maximum responses using the Finite Element Method (FEM). In the first iteration, an approximation of the Limit State Function (LSF) will be generated by using a Saturated Design (SD). The mean values of all Random Variables (RVs) in the normal variable space will be considered as center points. At the end of the first iteration, in the context of the First Order Reliability Method (FORM), the first reliability index (β), Most Probable Failure Point (MPFP), and sensitivity indexes (α_i) of all RVs will be available. RVs with low sensitivity indexes will be considered as deterministic at their mean values and the initial k number of RVs will be reduced to k_r. The next iteration will start by using k_r number of RVs and the previously obtained MPFP as center point. A new LSF will be reconstructed using SD. Utilizing the updated LSF, FORM will calculate β and MPFP. It will be used as center point for the next iteration of the novel probabilistic approach. The overall updating in center points will continue until β values for two consecutive iterations converge to a pre-established tolerance level. In the context of the probabilistic approach, in the final iteration, a Central Composite Design (CCD) will be used to generate a polynomial. Using the information on the required performance level, the corresponding LSF will be generated using the regression analysis. In general, it usually takes three to four iterations to reach convergence in terms of β values. Once the final β is found, the coordinates of the last checking point ($\boldsymbol{x}^*$) or MPFP will be calculated as:

$$\beta = \sqrt{(\boldsymbol{x}^*)^t(\boldsymbol{x}^*)} \quad (1)$$

Finally, based on the converged value of β, the corresponding probability of failure (p_f) can be estimated as:

$$p_f = \Phi(-\beta) = 1.0 - \Phi(\beta) \quad (2)$$

More information about the novel probabilistic approach can be found in Gaxiola-Camacho et al. (2017). A flowchart of the novel probabilistic approach is illustrated in Figure 3.

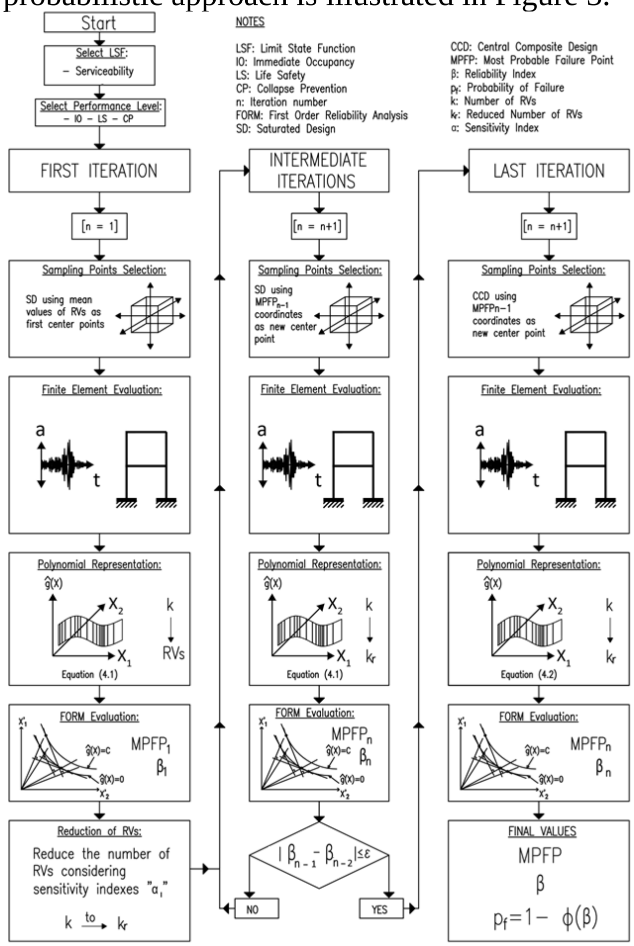

Figure 3: Novel reliability technique flowchart.

5. VALIDATION OF BBP

Before the application of the BBP in the calculation of structural risk using the novel probabilistic approach, it must be properly validated. To verify the accuracy of BBP, the 1994 Northridge earthquake is generated. Four locations in southern California are selected where real time histories of the 1994 Northridge earthquake are available. They are: (1) Santa Susana, (2) Alhambra – Fremont, (3) Littlerock – Brainard, and (4) Rancho Palos Verdes. Using the BBP v16.5.0 (SCEC, 2016) and GP method, simulations corresponding to the 1994 Northridge earthquake are performed for the above four stations. The rupture was generated using a magnitude of 6.7, fault length and width equal to 20 and 27 km, respectively. Strike, rake, and dip were considered as 122°, 105°, and 40°, respectively. Figure 4 illustrates the corresponding response spectra for real and simulated versions of the 1994 Northridge earthquake. Response spectra are plotted considering the N-S and E-W components of every station under study. It can be observed in Figure 4 that response spectra for simulated and real ground motions are very similar.

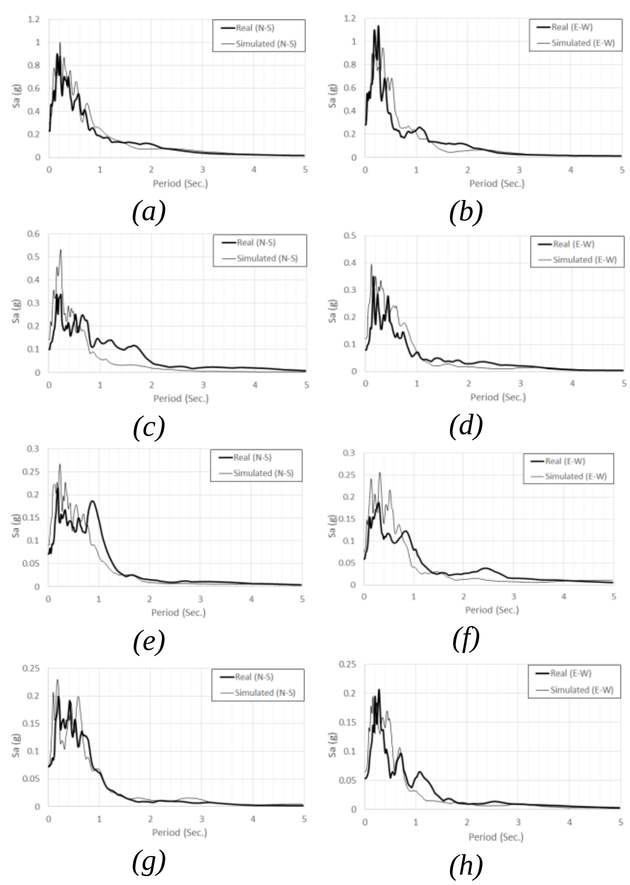

Figure 4: 1994 Northridge earthquake real and simulated response spectra: (a) Santa Susana N-S,

(b) Santa Susana E-W, (c) Alhambra - Fremont N-S, (d) Alhambra - Fremont E-W, (e) Littlerock – Brainard N-S, (f) Littlerock - Brainard E-W, (g) Rancho Palos Verdes N-S, and (h) Rancho Palos Verdes E-W.

To validate the BBP in terms of structural risk, the novel probabilistic approach is implemented. The 2-Story steel frame shown in Figure 5 is excited using real and simulated versions of the 1994 Northridge earthquake as illustrated in Figure 4. The risk in terms of β is summarized in Table 1 considering overall and inter-story drift of the second level.

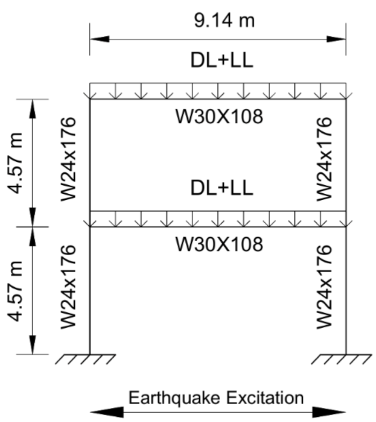

Figure 5: 2-story frame used for validations.

It can be observed in Table 1 that β and p_f are very similar for simulated and real versions of ground motions. In terms of mean reliability index (β_μ), it can be observed that the performance of the building is more critical for inter-story drift conditions. Based on the results presented in this section, the accuracy calculating structural risk of the BBP version v16.5.0 (SCEC, 2016) is validated.

Table 1: Structural reliability for real and simulated ground motions.

Station	Overall Lateral Drift		Inter-Story Drift	
	Real	Simulated	Real	Simulated
	β	β	β	β
Santa Susana N-S	3.6137	3.9556	3.0545	3.0810
Santa Susana E-W	3.8067	3.6250	3.4565	3.3591
Alhambra - Fremont N-S	4.2430	4.3176	4.1201	4.3594
Alhambra - Fremont E-W	5.2484	5.4095	5.4044	5.3108
Littlerock – Brainard N-S	3.8286	3.2042	3.8287	3.2146
Littlerock - Brainard E-W	4.2997	4.1296	3.8521	3.1554
Rancho Palos Verdes N-S	4.8866	4.6424	3.8442	3.3492
Rancho Palos Verdes E-W	3.5370	3.3994	3.8271	3.8622
β_μ (p_f)	4.1830 (1.43E-05)	4.0854 (2.20E-05)	3.9235 (4.36E-05)	3.7115 (1.03E-04)

6. APPLICATION OF BBP

As previously discussed, when nonlinear time domain analysis is required, it is common for structural engineers to face the problem of lack of ground motion records. It was verified in the previous section that the BBP v16.5.0 (SCEC, 2016) can be used for the proper generation of ground motions for a specific site. To demonstrate the applicability of the BBP, a set of ground motions is generated for a specific site in Los Angeles area. In this context, the 3-story steel frame illustrated in Figure 6 was designed for the Los Angeles zone, it is used as a case study.

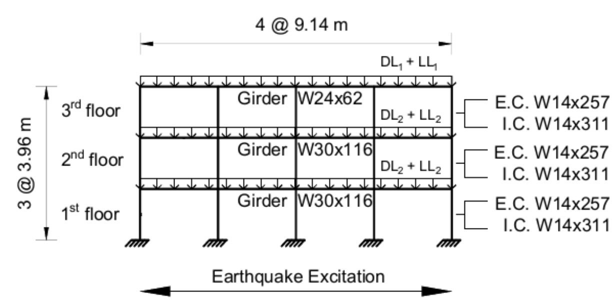

Figure 6: Story Building: (a) Plan view; (b) Elevation (E.C.=Exterior Columns; I.C.=Interior Columns).

Considering that an appropriate number of real ground motions are difficult to obtain for near-fault locations (Burks *et al.*, 2015), the Raymond Hill Fault located close to Los Angeles is considered in this study. The BBP is used for the proper simulation of ground motions at 16 stations placed around the building and fault location. Figure 7 illustrates the location of the building, stations, and fault.

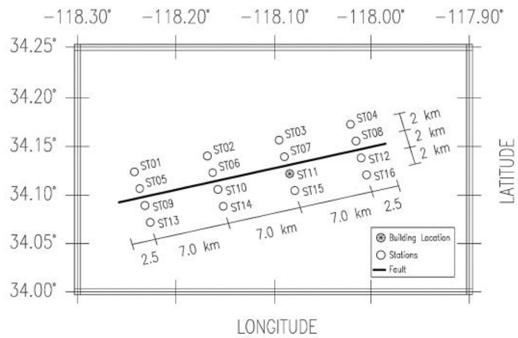

Figure 7: Stations, building, and fault location.

To simulate ground motions using the BBP, a description of the rupture is necessary. The seismic hazard analysis for the building location yields an earthquake magnitude equal to 6.7 (USGS, 2008). In addition, fault length and width were 26 and 20 km, respectively. Strike, rake, and dip are equal to 75°, 0°, and 90°, respectively. Six hypocenters were used to simulate the variability of their location in the rupture. Figure 8 illustrates the location of every hypocenter considered in this study.

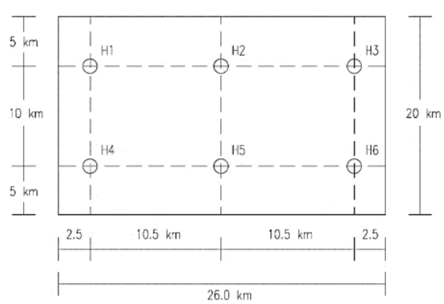

Figure 8: Location of hypocenters.

Considering six hypocenters, sixteen stations, and two components (N-S and E-W) per station, a total of 192 grounds motions were generated. For the sake of clarity, the corresponding response spectra of the simulated ground motions are plotted in Figure 9.

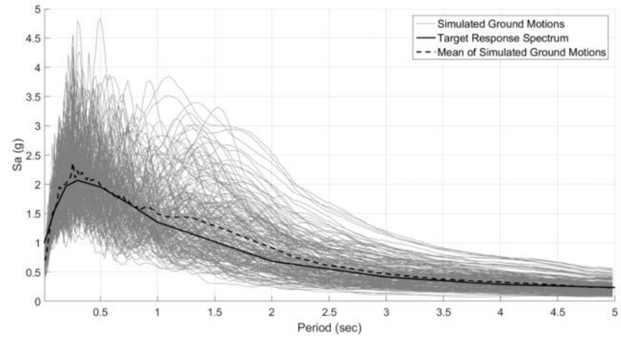

Figure 9: Simulated ground motions response spectra and target response spectrum.

Using the above set of simulated ground motions, 11 ground motion time histories were selected using as a target the Uniform Hazard Spectrum (UHS) with a probability of exceedance of 2% in 50 years (Azizsoltani *et al.*, 2018). UHS has been used by the engineering community as a suitable target response spectrum for seismic-resistant design over the last 20 years. It is the graphical representation of the spectral acceleration versus the period. In this sense, UHS represents the response spectrum of the site having the same rate of exceedance for the spectral acceleration at all periods. The generation of the UHS is performed using the United States Geological Survey (USGS) web application (USGS, 2008). The USGS application provides a data base for generating site-specific hazard curves in terms of spectral acceleration versus annual rate of exceedance for spectral periods of Peak Ground Acceleration (PGA) of 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 seconds. Using the site-specific hazard curves generated by the USGS application, information of the spectral accelerations for each period can be obtained.

Currently, the use of at least 7 site-specific ground motions is recommended by the ASCE 7-16 (2016) construction code. However, some other studies suggest considering at least 11 of such site-specific ground motions (Zimmerman *et al.*, 2017). In this study, 11 time histories scaled from the previously generated ground motion set (Figure 9) are selected. The scaling is generally done by matching the probabilistic ground motion response spectrum at the fundamental period of the structure (T). A Scale Factor (SF) close to 1 is generally desired (Watson-Lamprey & Abrahamson, 2006). However, SF can vary widely. It is recommended limiting the upper limit of SF up to a value of 4. The potential scaled site-specific time histories are ranked in terms of suitability to select only the most appropriate ones. To determine the suitability factor, T is considered to range between $0.2T$ and $2.0T$. ASCE 7-16 (2016) defines this range to be between $0.2T$ and $1.5T$ in section 16.1.3.1. However, Baker (2011) noticed large sensitivity of structures to the response spectra at highly nonlinear phases at periods longer than $1.5T$. Then, the period of the structure is considered to range between $0.2T$ and $2.0T$. This interval is subdivided into 40 equal subintervals to consider the information on the lower and upper bounds. The matching of ground motions for higher vibration modes is based on the lower bound, while the upper bound is used for matching ground motions at highly nonlinear phases. The total error is evaluated for each ground motion as the Square Squares Errors (SSE) as recommended by Jayaram *et al.* (2011). Finally, only 11 ground motions with the smallest SSE are considered for each suite of time histories and are considered for the reliability evaluation. The eleven ground motions response spectra, mean value of them, and target response spectrum are illustrated in Figure 10. They were selected for the 3-story steel frame (Figure 6) with T=0.85 seconds.

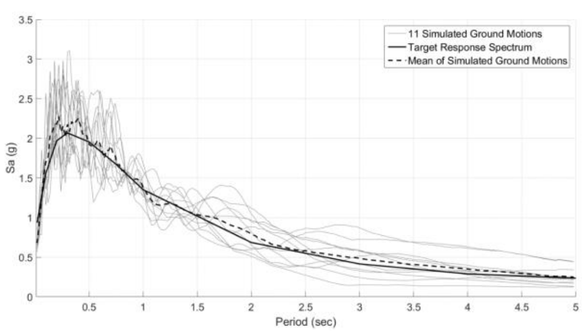

Figure 10: Response spectra of eleven selected ground motions and target response spectrum.

The 3-story steel frame is excited using the 11 selected ground motions. Reliability information is extracted with the novel probabilistic approach. Results are summarized in Table 2. In general, it can be noted that the structural reliability in terms of β and p_f is adequate. For all cases, p_f is smaller than 10% satisfying the main intent of the code. Hence, where there are not enough real records in the zone of interest, the BBP is a reliable computational tool for the proper simulation of them.

Table 2: Structural reliability of 3-story frame using 11 simulated ground motions.

EQ	**Station**	**Scale Factor**	**Overall Lateral Drift**	**Inter-Story Drift**
			β	β
1	Stat. 15 - Hyp. 01 - NS	1.16	4.5801	4.0993
2	Stat. 15 - Hyp. 02 - NS	1.17	5.7207	4.3864
3	Stat. 16 - Hyp. 04 - EW	1.31	5.6494	4.8015
4	Stat. 09 - Hyp. 06 - NS	0.92	4.4624	3.9622
5	Stat. 13 - Hyp. 04 - EW	1.01	5.0137	4.2825
6	Stat. 10 - Hyp. 03 - EW	1.30	4.7445	4.7030
7	Stat. 04 - Hyp. 06 - EW	1.12	4.7523	4.9018
8	Stat. 08 - Hyp. 03 - EW	1.02	4.9477	4.2880
9	Stat. 14 - Hyp. 02 - NS	1.06	5.2112	4.3837
10	Stat. 15 - Hyp. 06 - NS	0.84	4.5904	4.0513
11	Stat. 02 - Hyp. 06 - EW	1.15	5.9262	5.3427
		β_μ (p_f)	5.0544 (2.1587E-07)	4.4729 (3.8583E-06)

7. CONCLUSIONS

The BBP version v16.5.0 (SCEC, 2016) was validated. It was demonstrated to be a viable computational tool for the simulation of ground motions. Time histories of ground motions were simulated for the 1994 Northridge earthquake. Response spectra were compared for simulated and real versions. Since response spectra were found to be very similar, the accuracy of the simulations was validated. The application of the BBP was demonstrated by generating a set of ground motions representative of the seismic hazard of the Los Angeles area. A target response spectrum was calculated following the recommendations of the code (ASCE 7-16, 2016) and USGS (USGS, 2008). Based on the structure under consideration, target response spectrum, and the set of generated ground motions, eleven time histories were selected. A 3-story steel frame was subjected to the eleven selected ground motions and its corresponding reliability information was extracted using a novel probabilistic approach. The results verify and demonstrate the potential of BBP for the generation of simulated ground motions as well as the compounding beneficial effects of the novel probabilistic approach.

8. REFERENCES

ASCE/SEI 7-16 (2016), "Minimum design loads for buildings and other structures", American Society of Civil Engineers (ASCE), Reston, VA, USA.

Azizsoltani, H., Gaxiola-Camacho, J. R., & Haldar, A. (2018). Site-specific seismic design of damage tolerant structural systems using a novel concept. *Bulletin of Earthquake Engineering*, *16*, 3819-3843.

Baker, J. W. (2011). Conditional mean spectrum: Tool for ground-motion selection. *Journal of Structural Engineering*, *137*(3), 322-331.

Burks, L. S., Zimmerman, R. B., & Baker, J. W. (2015). Evaluation of hybrid broadband ground motion simulations for response history analysis and design. *Earthquake Spectra*, *31*(3), 1691-1710.

Burks, L. S., Zimmerman, R. B., & Baker, J. W. (2015). Evaluation of hybrid broadband ground motion simulations for response history analysis and design. *Earthquake Spectra*, *31*(3), 1691-1710.

Cacciola, P., & Zentner, I. (2012). Generation of response-spectrum-compatible artificial earthquake accelerograms with random joint time–frequency distributions. *Probabilistic Engineering Mechanics*, *28*, 52-58.

Gaxiola-Camacho, J. R., Azizsoltani, H., Villegas-Mercado, F. J., & Haldar, A. (2017). A novel reliability technique for implementation of performance-based seismic design of structures. *Engineering Structures*, *142*, 137-147.

Graves, R. W., & Pitarka, A. (2010). Broadband ground-motion simulation using a hybrid approach. *Bulletin of the Seismological Society of America*, *100*(5A), 2095-2123.

Jayaram, N., Lin, T., & Baker, J. W. (2011). A computationally efficient ground-motion selection algorithm for matching a target response spectrum mean and variance. *Earthquake spectra*, *27*(3), 797-815.

Mai, P. M., Imperatori, W., & Olsen, K. B. (2010). Hybrid broadband ground-motion simulations: Combining long-period deterministic synthetics with high-frequency multiple S-to-S backscattering. *Bulletin of the Seismological Society of America*, *100*(5A), 2124-2142.

SCEC (2016). Broadband Platform. Southern Califorinia Earthquake Center (SCEC). URL https://scec.usc.edu/scecpedia/Broadband_Platform.

Schmedes, J., Archuleta, R. J., & Lavallée, D. (2010). Correlation of earthquake source parameters inferred from dynamic rupture simulations. *Journal of Geophysical Research: Solid Earth*, *115*(B3).

Shields, M. D. (2015). Simulation of spatially correlated nonstationary response spectrum–compatible ground motion time histories. *Journal of Engineering Mechanics*, *141*(6), 04014161.

USGS (2008). Interactive Deaggregations (beta). United States Geological Survey (USGS). URL https://earthquake.usgs.gov/hazards/interactive.

Walling, M., Silva, W., & Abrahamson, N. (2008). Nonlinear site amplification factors for constraining the NGA models. *Earthquake spectra*, *24*(1), 243-255.

Watson-Lamprey, J., & Abrahamson, N. (2006). Selection of ground motion time series and limits on scaling. *Soil Dynamics and Earthquake Engineering*, *26*(5), 477-482.

Yamamoto, Y., & Baker, J. W. (2013). Stochastic model for earthquake ground motion using wavelet packets. *Bulletin of the Seismological Society of America*, *103*(6), 3044-3056.

Zimmerman, R. B., Baker, J. W., Hooper, J. D., Bono, S., Haselton, C. B., Engel, A., ... & Jalalian, A. (2017). Response history analysis for the design of new buildings in the NEHRP provisions and ASCE/SEI 7 standard: Part III-Example applications illustrating the recommended methodology. *Earthquake Spectra*, *33*(2), 419-447.