Application of Conditional Mean Spectrum in the Seismic Assessment of a Braced Frame Steel Structure

P Jayarajan*

Department of Civil Engineering, National Institute of Technology, Calicut, India

*puttatt1@gmail.com

Abstract. Detailed engineering of critical infrastructure and tall buildings require that their response be estimated from nonlinear response history analysis (NLRHA) by subjecting the structure to suites of earthquake accelerograms. Selection of ground motion records due to future earthquake events represents an important step in the robust assessment of structural response. As per the current practice, both site-specific uniform hazard spectrum (UHS) and conditional mean spectrum (CMS) are employed as the target spectra for ground motion record selection. The CMS approach is superior considering that it represents realistic seismic events and also consider the multiple natural periods of the structure. The paper presents the application of conditional mean spectrum in the seismic assessment of an eight-story ordinary braced steel structure built on an example site. The NLRHA was conducted using the ground motions spectrally matched to the CMS at different conditioning periods. It was found that the CMS spectrally matched to larger modal period always result in larger seismic demands. A comparison was also made between seismic demands obtained from UHS & CMS indicating that the structural response parameters are almost the same in both cases except the story shears & drifts which is dominated by UHS in lower floors and by CMS in upper floors.

1. Introduction

The nonlinear response history analysis (NLRHA) is being widely used by practicing engineers for the design of tall building structures & critical infrastructure and development of suitable retrofit schemes for existing buildings. It is also extensively used in performance-based earthquake engineering (PBEE) assessment, wherein structures subjected to suites of ground motions representing multiple hazard levels are assessed for different performance objectives. The nonlinear dynamic procedures are more accurate than the static procedure as the effects of higher modes of vibration are inherently accounted and considers the material inelastic response in the performance assessment. In cases, where acceptance criteria for a linear analysis could not be achieved, nonlinear procedures can be used [1]. However, in NLRHA the structure responses are highly influenced by the characteristics of selected ground motions & the structural model used to represent inelastic behaviour.

Selection of suitable ground motion records is a challenging task in NLRHA considering that the calculated seismic demands are highly influenced by the ground motion characteristics. Further the suite of ground motions used for analysis shall be a representative of the site seismic hazard. PEER[2] provides a detailed account of various ground motion selection and modification methods including the uniform hazard spectrum (UHS) and conditional mean spectrum (CMS). The ground motion selection procedure in various codes are currently based on a target spectrum. ASCE 7-16[3] requires that either a code specified response spectrum for maximum considered earthquake (MCE) derived from a uniform hazard spectrum (UHS) or site-specific conditional mean spectrum (CMS) developed for predominant periods of the structure could be used as a target spectrum for selection of ground motion records. CMS could be used to address the conservatism inherent in UHS. Normally the periods of vibration of the structure are chosen as the conditioning periods for the development of CMS. The effect of conditioning
periods on the shape of CMS and structural response is studied in detail [4]. The use of CMS for selection of ground motion records and tools available for the automation of CMS calculations are provided [5].

The present study investigates the application of conditional mean spectrum (CMS) in NLRHA to arrive at various structural response parameters for a concentric braced steel structure built in an example site. The conditioning periods for CMS were based on natural periods obtained from a modal analysis. Three suites of ground motions were used, two suites spectrally matched to the CMS at conditioning periods and the third matched to the developed site specific UHS. The structural responses obtained from two conditioning periods are compared to study the influence of higher modes. Finally, responses obtained from CMS are compared with UHS. The response parameters include the story displacement, story shear, story drift and story moment.

2. Example site

The example site has two active faults which shall be considered in the probabilistic assessment of various ground motion intensity measures. The fault $F_1$ at a distance $R = 10$ km from the site produce earthquakes of magnitude $M = 6.5$ with an annual occurrence rate ($\lambda$) of $0.01$. The corresponding values for fault $F_2$ are $M = 7.5$, $R = 20$ km & $\lambda = 0.002$. Both events have an assumed strike slip mechanism with the rupture extending the entire length of faults. The site is characterized by shallow soil followed by rock strata so that the effect of local site amplification need not be considered.

3. Description of structure

An eight-story steel braced structure considered for the study is shown in figure 1. The structure is 17x17m in plan and 28 m in height. The storey height is maintained at 3.5m at all levels. The seismic force resisting system consists of two perimeter braced frames in each direction. The interior columns of the structure are designed only for gravity loads and do not contribute to seismic resistance. The structural floor at all levels essentially consists of corrugated reinforced cement concrete (RCC) deck slab supported on secondary steel beams. The deck slab ensures a diaphragm action and is effective in transferring the seismic shear to the peripheral braced frame. Permanent gravity load (G) of 3.0 kN/m² and a live load (Q) of 5.0 kN/m² is considered on all floors. A load combination of G+0.3Q is used for the computation of lumped masses at all floor levels. The modal response spectrum analysis is performed for estimation of natural periods, mass participation ratios and the seismic base shear. The UHS developed for the site is used as a target spectrum. Considering the structural symmetry, a 2-D frame analysis is deemed to be satisfactory. The behaviour factor (q) is taken as 4.0 as per Eurocode 8 (EC8) [6] corresponding to a concentric braced frame with diagonal bracings. European steel section profiles are used for the structure. The structural members are sized based on the results of elastic analysis to be verified later for capacity requirements. The modal analysis results are given in Table 1.

![Figure 1. Structure details.](image-url)
4. Development of site-specific uniform hazard spectrum (UHS)

A uniform hazard spectrum (UHS) represents a spectrum developed in such a way that the spectral acceleration values at different periods has an equal exceedance probability set according to the design objective. The UHS therefore has an inherent disadvantage that it does not correspond to single earthquake event and therefore would be conservative. However, a UHS would be a better choice to select the spectral acceleration corresponding to the target periods for further development of a realistic conditional mean spectrum. Different stages followed in the development of UHS are given below.

4.1. Probabilistic seismic hazard analysis (PSHA)

A detailed PSHA study is performed for the example site to arrive at the site-specific uniform hazard spectrum (UHS) for a preselected probability of exceedance. PSHA has the advantage that it considers various uncertainties in the occurrence of earthquakes and includes the effect of earthquake size onto the ground-motion characteristics to provide the seismic hazard at a site. PSHA is dealt in great detail [7] & National Research Council Report [8]. The basic PSHA equations used for the present study are

\[ P(IM > x) = \int_{m_{min}}^{m_{max}} \int_{r_{min}}^{r_{max}} P(IM > x | m, r) f_M(m) f_R(r) \, dr \, dm \]

\[ \lambda(IM > x) = \lambda(M > m_{min}) \int_{m_{min}}^{m_{max}} \int_{r_{min}}^{r_{max}} P(IM > x | m, r) f_M(m) f_R(r) \, dr \, dm \]

where \( IM \) indicates the intensity measure such as peak ground acceleration (PGA), spectral acceleration (SA) used in the analysis and \( P(IM>x|m,r) \) denotes the probability of exceeding an IM intensity level \( x \) calculated from ground motion prediction equation (GMPE) as

\[ P(IM > x | m, r) = \int_{\ln IM}^{\infty} \frac{1}{\sigma_{\ln IM} \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\ln u - \ln IM}{\sigma_{\ln IM}} \right)^2 \right] \, du \]

\( \ln IM \) & \( \sigma_{\ln IM} \) are the mean and standard deviation of the GMPE model. \( f_M(m) \) and \( f_R(r) \) represent probability density functions associated with magnitude and distance, \( \lambda(M>m_{min}) \) is the occurrence rate of earthquakes having magnitude greater that \( m_{min} \) from the source and \( \lambda(IM>x) \) is the rate of \( IM>x \).

For multiple sources,

\[ \lambda(IM > x) = \sum_{i=1}^{n_{sources}} \lambda(M_i > m_{min}) \int_{m_{min}}^{m_{max}} \int_{r_{min}}^{r_{max}} P(IM > x | m, r) f_{M_i}(m) f_{R_i}(r) \, dr \, dm \]

where \( n_{sources} \) represents the number of sources and \( M_i \) and \( R_i \) corresponds to the magnitude and distance for source \( i \).

4.2. Ground motion prediction equations (GMPE)

GMPEs provide the mean or median estimate and the associated probability distributions for earthquakes characterized by their magnitude, source-to-site distance considering the soil & geologic conditions at the site. They represent a critical input parameter for the PSHA. A brief review of GMPEs developed in the period 1964-2010 is available [9]. The most desirable feature in a GMPE is its capability to furnish accurate estimate of ground motion considering a minimum set of parameters. The Abrahamson-Silva 2008 (AS08) GMPE model being more complex with the over parameterization, a much simpler and realistic AS97 model [10] is used in the present study. The values of coefficients required for median model predictions and standard deviation are taken from AS97 model. The median spectral acceleration obtained from GMPE for the site is shown in figure 2. The pronouncing effect of large magnitude earthquakes in the long period range is clearly visible. The hazard curves showing the relation between

### Table 1. Dynamic Characteristics of the structure.

| Mode | Period (T) (sec) | Modal participation ratio (MPR) | Cumulative MPR | (Sa/g)-UHS | Elastic EQ shear (kN) | Design EQ shear (kN) |
|------|-----------------|---------------------------------|---------------|------------|----------------------|---------------------|
| 1    | 1.80            | 0.709                           | 0.709         | 0.286      | 896.3                | 224.1               |
| 2    | 0.55            | 0.204                           | 0.913         | 0.067      | 765.8                | 191.5               |
| 3    | 0.30            | 0.046                           | 0.959         | 1.667      | 257                  | 64.3                |
the spectral accelerations and associated rates of exceedance shall be constructed at multiple periods for the development of UHS. A typical hazard curve generated at a period of $T=1$ sec. is shown in figure 3.

![Figure 2. Median spectral acceleration-GMPE.](image1)

![Figure 3. Hazard curve for $S_a$ at $T=1$ sec.](image2)

4.3. **Uniform hazard spectrum (UHS)**
Using the hazard curves constructed for example site for different periods, a UHS computed for a specified rate of exceedance is developed. The target probability of exceedance equal to 10 % in 50 years (Return period=475 years) is selected to meet the “No-collapse requirement” as specified Eurocode 8[6]. The UHS is represented in figure 4. All calculations for UHS are performed using engineering math software Mathcad [11].

![Figure 4. UHS for the example site.](image3)

5. **Conditional mean spectrum (CMS)**
The CMS provides the mean response spectrum associated with a ground motion corresponding to $(M, R, \epsilon)$ values that results in a target spectral acceleration at preselected conditioning period. The values of epsilon ($\epsilon$) at a period represents the variation of the ground motion’s spectral value with respect to the one obtained from GMPE. The CMS constructed for a target period therefore corresponds to a single earthquake event having the same target spectral acceleration and thereby eliminates the inherent disadvantage with UHS. The CMS incorporates both site and structure characteristics in its formulation. A detailed procedure for the construction of CMS is provided [12]. The conditioning periods ($T^*$) for the development of CMS are taken as 1.50 and 0.50 s that are closer to the modal periods of the structure 1.80 and 0.55 s respectively. The CMS at these conditioning periods are given in figure 5.
6. Nonlinear response history analysis (NLRHA)

The concentric braced frame (CBF) structure in the present study sized for elastic forces is verified for various capacity design criteria requirements laid out in chapter 6 of EC8[6] for dissipative structures. This requires identifying, designing the dissipative zones and ensuring their occurrence at predefined locations and avoidance of elastic instabilities at non-dissipative zones. The diagonal braces are identified as dissipative members and the connected column members are checked for various capacity requirements. In order to ensure sequence of plastic hinging and global yield behaviour and to arrive at a realistic estimate of behaviour factor (q) a nonlinear static analysis (pushover analysis) is first performed as per the guidelines in EC8. The generalized component force - deformation relations for modelling the inelastic behaviour in tension diagonals are taken from ASCE standard ASCE/SEI 41-17 [1] and shown in figure 6. The resulting pushover curve shown in figure 7 confirms the capacity and ductility of the designed structure. As per FEMA-356[13], the structural performance is monitored through the maximum inter-story drift with associated values of 0.5%, 1.5% & 2.0% for braced steel frames corresponding to Immediate Occupancy (IO), Life Safety (LS) and Collapse prevention (CP) levels. The structure is capable of undergoing drifts well above 3.5% demonstrating its deformation capacity. The development of plastic hinges as shown in figure 8 were observed only in bracing members, ensuring the energy dissipation mechanism as envisaged in the design. Further, the achieved value of behaviour factor (q) of 5.48 calculated as per ATC-19[14] is higher than the assumed value of 4.0 ensuring the superior ductility characteristics. All linear, static nonlinear and nonlinear response history analysis are performed using finite element structural analysis software SAP2000[15].

Figure 6. Generalized force-deformation relation.  
Figure 7. Pushover curve.
The spectral matching and the selection of ground motion records are done as per the guidelines in ASCE 7-16[3]. Two suites of records each consisting of seven numbers of ground motions spectrally matched to the conditional mean spectrums CMS (T$_1$) and CMS (T$_2$) are used for NLRHA. The recorded ground motions with site characteristics similar to the example site are obtained from PEER (Pacific Earthquake Engineering Research Centre) Strong Ground Motion Database [16]. The target conditional mean spectra and the spectra associated with the selected ground motions (GMs) along with their mean are shown in figure 9.

7. Results

The results obtained from NLRHA are presented in terms of structural response parameters such as story displacements, story drift ratio, story shear and moments. The responses are studied in two stages, first a comparison between CMS responses and second between CMS and UHS. Figure 10 shows that the CMS conditioned at larger period (fundamental period) i.e. CMS(T$_1$) provide a larger response for all parameters studied and govern the envelope of CMS(T$_1$) and CMS(T$_2$). However, this observation may not be valid for tall structures where the higher mode effects govern the response parameters at higher story levels. A comparison between CMS and UHS shown in figure 11 indicates that, the structural response parameters are almost the same in both cases except the story shears and drifts which is dominated by UHS in lower floors and by CMS in upper floors.

Figure 8. Plastic hinge pattern in pushover analysis (a) IO-level (b) LS-level (c) CP-level.

Figure 9. Spectrally matched ground motions (GMs).
Figure 10. Structural response parameters for CMS at different conditioning periods.
8. Conclusions
The implementation of conditional mean spectrum (CMS) to estimate the seismic demands of an eight-story steel structure provided with ordinary concentric braced frame situated at an example site was investigated in the present study. The structural response parameters included storey displacement, inter-story drift, story shear and bending moment. The responses were compared between CMS conditioned at different natural periods of the subject structure. The seismic demands obtained through CMS and UHS were also compared. The study shows that the CMS conditioned at larger modal period (fundamental period) govern the structural response as compared to the one conditioned at higher modes. However, for tall structures, CMS conditioned at higher modes may govern certain structural response quantities. It is also observed that for the structure investigated, the UHS and CMS provide almost the same seismic demands except the story shears and drifts which is dominated by UHS in lower floors and by CMS in upper floors.

9. References
[1] ASCE/SEI 41-17 2017 Seismic Evaluation and Retrofit of Existing Buildings (American Society of Civil Engineers/Structural Engineering Institute)
[2] Haselton C B 2009 Evaluation of ground motion selection and modification methods: predicting median inter-story drift response of buildings PEER Report 2009/01 (Pacific Earthquake Engineering Research Centre University of California Berkeley)
[3] ASCE/SEI 7-162016 Minimum Design Loads for Buildings and Other Structures (American Society of Civil Engineers/Structural Engineering Institute)
[4] Azarbakht A and Ghodrati A R 2018 The dependence of conditional spectra on the choice of target periods Scientia Iranica Transaction A: Civil engineering 25 1–10
[5] Baker J W 2011 Ground motion selection for the performance-based engineering, and the conditional mean spectrum as a selection tool Proc. of the 10th Pacific Conf. on Earthquake Engineering-Building an Earthquake Resilient Pacific (Sydney)
[6] EN 1998-12004 Eurocode 8 Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions, and Rules for Buildings (European Committee for Standardization Brussels)
[7] Kramer S L 2003 Geotechnical Earthquake Engineering Prentice-Hall International Series in Civil Engineering and Engineering Mechanics (Pearson Education: India)
[8] National Research Council Report 1988 Probabilistic Seismic Hazard Analysis ed. Washington D.C. (National Academy Press)
[9] Douglas J 2011 *Ground-motion prediction equations 1964-2010 PEER Report 2011/102* Pacific Earthquake Engineering Research Center College of Engineering (University of California Berkeley)

[10] Abrahamson NA and Silva WJ 1997 Empirical response spectral attenuation relations for shallow crustal earthquakes *Seismological Research Letters* **68** 94–127

[11] Mathcad Professional The worldwide standard for technical calculations ([https://www.ptc.com/en/products/mathcad](https://www.ptc.com/en/products/mathcad))

[12] Baker J W 2011 Conditional mean spectrum: tool for ground motion selection *Journal of Structural Engineering* **137** 322–31

[13] FEMA 356 2000 *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (American Society of Civil Engineers Federal Emergency Management Agency: Washington, DC)

[14] ATC-19 1995 *Structural Response Modification Factors* (Applied Technology Council: Redwood City, California)

[15] SAP2000 version 20 Linear and nonlinear static and dynamic analysis of three-dimensional structures (Computer and Structures: Berkeley, CA)

[16] Peer Strong Motion Database2013/14 ([https://peer.berkeley.edu/ngawest2](https://peer.berkeley.edu/ngawest2) and [https://peer.berkeley.edu/ngaeast](https://peer.berkeley.edu/ngaeast))

**Acknowledgements**

The author would like to thank Pacific Earthquake Engineering Research Centre (PEER) for providing access to ground motion database and tools for searching, scaling and downloading ground motion data.