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PREDICTION OF TALL BUILDING CRITICAL DISPLACEMENT DEMANDS DUE TO PULSE-LIKE NEAR FIELD GROUND MOTIONS

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ABSTRACT: Performance based seismic design of a tall building located in the proximity of active faults requires a thorough assessment of the displacement demands imposed by pulse like near field ground motions. In this context, the effects of ground motion directionality are an important factor to consider given the variability they introduce into the input motion and the building response. An approach to estimate the critical displacement is to conduct nonlinear response history analysis to ground motions rotated at small angle increments, which is computationally expensive and not practical for performance based design. To overcome this limitation we present a practical method to estimate the critical displacement demands along the structural axis. The method is useful to make informed decisions regarding the orientation of ground motions pairs used for nonlinear response history analysis and performance evaluation of buildings. A step-by-step application of the method to a case study building is given. We expect this study will help to bridge the gap in the assessment of tall buildings seismic demands from pulse like near field ground motions and help to improve current building code provisions.

1. Introduction

The seismic performance assessment of modern tall buildings at the design level is increasingly relying on nonlinear response history analyses and the evaluation of this response against performance acceptance criteria. The definition of the seismic input for these nonlinear analyses requires a process of selecting, orienting and scaling a suite of design ground motions compatible with the expected ground shaking.

Currently, limited guidance is available to earthquake engineers on how to carry out the process of seismic input definition for nonlinear response history analysis when dealing with near field ground motions that contain strong velocity pulses. Many members of the earthquake engineering community agree on this issue (Haselton et al., 2012).

The study of the effects that ground motion directionality has on seismic response of buildings has been going on for many decades already. The main concern has been to determine the maximum building's response when the seismic input has its critical angle of incidence. Currently these effects are at the center of ongoing debate among earthquake engineering professionals and researchers. A research program on this topic has taken place within the University of British Columbia (UBC), at the Earthquake Engineering Research Facility. This paper presents an overview of the method proposed to estimate the critical displacements. Figure 1 shows a summary of the method proposed.

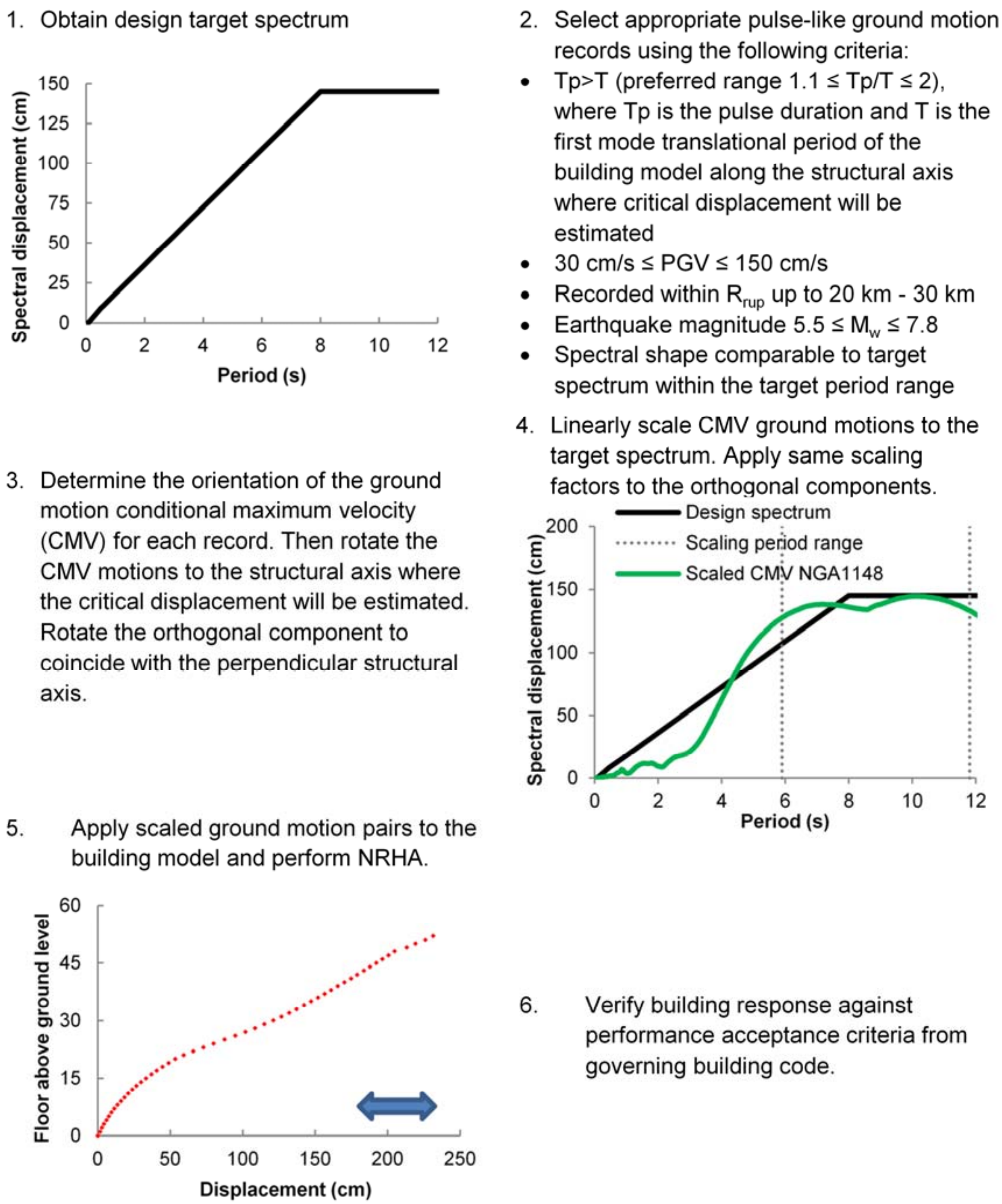


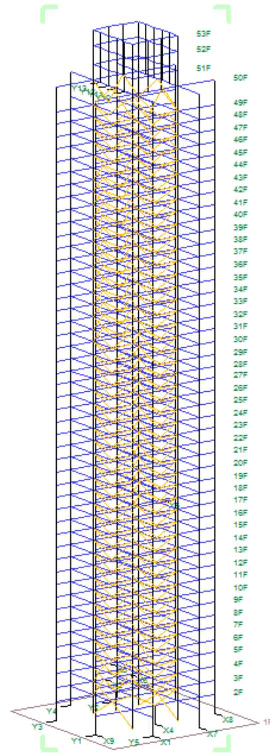
Fig. 1 – Flowchart of the CMV method within the framework of performance based design

1.1. Case study description

A step-by-step application of the CMV method to determine the critical displacement response of a case study 52 storey steel frame building is presented in the following example. Construction of this building for office occupancy ended in 1990. A spine structure is the structural system used for this 218m building located in downtown Los Angeles. The spine is a concentrically rectangular braced core that runs uninterrupted within the building and consists of four core steel columns that are tied together by beams and diagonal braces. Outrigger beams couple the perimeter outrigger columns with the braced core.

A picture of this building and a 3D view of the computer model appear in Figure 2. This building's floor plan has an octagon shape and exhibits many setbacks above the 36th floor. Ventura and Ding (2000) created the computer model of this building for a previous study that investigated this building's nonlinear response to near-field pulse-like motions. CANNY (Li, 2015) program was used to create the model. The model does not include the setbacks. Table 1 summarizes the dynamic properties of the computer model. For further details about this model, please refer to Ventura and Ding (2000).

(a) Building picture



(b) Model view

Fig. 2 – Picture and computer model representation of 52-storey steel building

Table 1 - Dynamic properties of 52-storey computer model

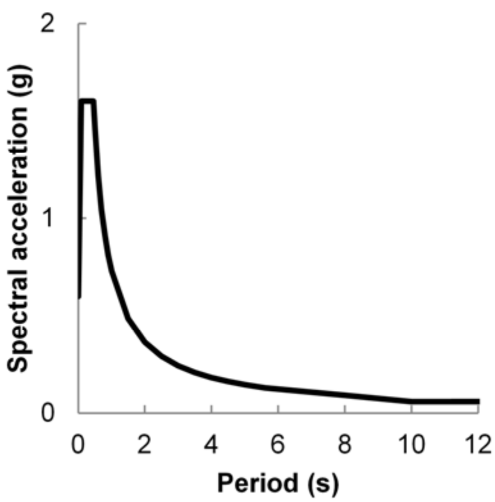
Mode	Natural Period (s)	Mode shape	Modal Damping (%)
1	5.90	Translational X-direction	2.00%
2	5.50	Translation Y-directional	1.93%
3	4.74	Torsional	1.82%
4	1.83	Translational X-direction	2.00%
5	1.74	Translation Y-directional	2.06%
6	1.71	Torsional	2.08%

2. Method application

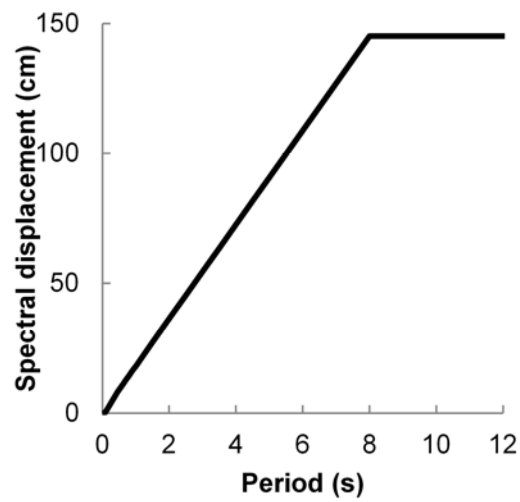
2.1. Definition of target spectrum

In this example, we utilize the acceleration design spectrum in downtown Los Angeles at site class C from the NHERP 2009. The contribution to the seismic hazard in Los Angeles and the design spectrum come from different faults beneath the city among other seismic sources and includes near field effects. The spectral ordinates are available in the USGS website in the following link http://earthquake.usgs.gov/hazards/designmaps/usdesign.php. The 5% damped design spectrum shown in Figure 3a includes maximum direction response factors.

For cases when design spectrum is a geometric mean, we use approximate conversion factors to convert it into a maximum direction spectrum (Watson-Lamprey and Boore, 2007). At periods shorter than 0.1s the ordinates should be increased by a conversion factor of 1.2, at periods longer than 1.0s the conversion factor is 1.3 and the factor is interpolated for intermediate periods.



(a) Acceleration design spectrum



(b) Displacement design spectrum

Fig. 3 – Design spectrum at Los Angeles Downtown (5% damping ratio)

2.2. Ground motion selection

The ground motion records used in this study are available from the PEER Ground Motion Database available at the Pacific Earthquake Engineering Research Center website (PEER, 2015). Additional guidance about pulse-like records contained in the database is available in recent reports that have identified pulse-like ground motions (NIST, 2011; Shahi, 2013).

A preliminary search in these reports resulted in a set of over 30 ground motions. An interesting observation from the all records considered in the preliminary selection is that strong velocity pulses were recorded up to distances of 30km and even farther. Then we did a careful inspection of each ground motion record to ensure they would meet the criteria outlined in Figure 1.2. Upon filtering the preliminary set with the recommended criteria, we implemented steps 3 and 4 given in Figure 1 to ensure the response spectra of the selected motions provides a close approximation to the design spectrum.

The result of this process is a set of 14 ground motions pairs, divided in two suites of seven ground motion pairs. The critical displacement in X and Y directions are going to be determined using each suite separately. Tables 2 and 3 list the records contained in each suite. Several records from 1999 Chi Chi earthquake are listed. In the selected ground motions, there are 5 pairs recorded at distances between 20 and 30 km, which contain strong velocity pulses of long duration with peak ground velocity greater than 40 cm/s. The ground motion NGA1487 recorded at 35km from the rupture was included because the response spectrum matches closely the target spectrum. The motion NGA1528 recorded at the closest station to the rupture has a peak ground velocity of 77 cm/s.

Table 2 – Selection of ground motions for suite 1

Record sequence number	Station	Distance Rrup (km)	Magnitude	Earthquake Event
285	Bagnoli Irpinio	8.2	6.9	1980 Irpinia
900	Yermo Fire Station	23.6	7.3	1992 Landers
1148	Arcelik	13.5	7.8	1999 Kocaeli
1487	TCU047	35	7.6	1999 Chi Chi
1494	TCU054	5.3		
1531	TCU104	12.9		
6966	SHLC	22.3	7	2010 Darfield

Table 3 – Selection of ground motions for suite 2

Record sequence number	Station	Distance Rrup (km)	Magnitude	Earthquake Event
180	El Centro array #5	4	6.5	1979 Imperial Valley
1158	Duzce	15.4	7.5	1999 Kocaeli
1485	TCU045	26	7.6	1999 Chi Chi
1528	TCU101	2.1		
1548	TCU128	13.1		
5832	Tamaulipas	26.6	7.2	2010 El Mayor-Cucapah
6887	CBGS	18.1	7	2010 Darfield
6942	NNBS	26.8	7	

2.3. Identification of the Conditional Maximum Velocity (CMV)

To examine each ground motion pair we use the CMV method, which includes the following steps:

Step 3.A. Obtain the first mode translational period of the building along the structural axis where the critical displacements will be determined.

Step 3.B. For the pulses contained the ground motion, represent in a single polar plot the orientation dependence of the velocity pulse duration. Identify the range of orientations where the duration of the pulse is longer than the first mode translational period of the building.

Step 3.C. Within this range of orientations, identify the orientation of maximum ground velocity. This defines the orientation of the conditional maximum velocity for the ground motion pair.

Step 3.D. Then, rotate the ground motion pair to apply the CMV ground motion along the structural axis where the critical displacements will be determined.

2.4. Ground motion scaling

Linearly scaling a ground motion to the target spectrum preserves the frequency content of the ground motion and the duration of the velocity pulse, affecting only the intensity of the motion. If the same scaling factor modifies both orthogonal components, then the directionality of the motion remains unchanged and the application of the CMV method is feasible. For this reason, linear scaling of pulse-like ground motions to closely approximate to the target spectrum is preferred over spectral matching techniques, which may significantly change the frequency content of the motion, changing the amplitude and duration of the velocity pulses.

2.4.1. Scaling factors

There are no generally accepted limits on the amplitude of the scaling factors that modify a ground motion record. However, when using pulse-like ground motions the peak ground velocity should be limited not to exceed 100 to 150 cm/s, a theoretical limit range determined by Ambraseys (1969) and Brune (1970). Overlooking the limit of 150 cm/s, may provide input ground motions with unrealistic PGV.

A maximum scaling factor of 2 is recommended to adjust the response spectrum of each ground motion; otherwise, if the scaling factor is too large another pulse-like ground motion having larger peak ground velocity should be selected to minimize the amplitude scaling factor. At the lower bound, we recommend a minimum scaling factor of 0.70. These limits, are suggested since there is evidence that large scaling factors introduce bias on the nonlinear dynamic response of buildings (Bazzurro and Luco, 2006).

In the case study, the scaling factor for each ground motion was determined to match the area underneath the design spectrum bound within the target period range, with the area of the response spectrum within the same period range.

2.4.2. Target period range

Different recommendations are available for the appropriate target period range. The standard ASCE/SEI 7-10 prescribe the target period range for scaling of ground motions from 0.2T to 1.5T, where T is the calculated first mode translational period. Haselton et al. (2012) recommended to scale ground motions in the range of $0.2T_{1,min}$ to $2T_{1,max}$ for shear wall buildings and $0.2T_{1,min}$ to $3T_{1,max}$ for moment resisting frame buildings, where $T_{1,min}$ and $T_{1,max}$ correspond to the shorter and longer first mode translational periods along the two horizontal axes of the building. The recommended range extends to periods shorter than T to ensure the contribution of higher modes to the seismic response is properly considered.

The recommendation from the Los Angeles Tall Buildings Structural Design Council (LATBSDC, 2014) is to scale ground motions, to capture properly the dynamic response of buildings in each significant mode. The recommended the target period range is from 0.1T to 1.5T.

Since the goal of the CMV method is to estimate critical displacement response and the first mode contributes significantly to this response, the target period range will not include the periods that correspond to higher modes. The proposed period range for scaling of ground motions is from T to 2T. Herein, the period T corresponds to the translational first mode in the direction of the structural axis where the critical displacement response will be determined.

The application of these criteria to scaling the two suites of ground motions, results in the spectra of CMV input motions in X and Y direction as shown in Figures 3 and 4. For clarity purposes, we do not show the response spectra of the orthogonal components. In the example that we present, the target period range for scaling each suite is different, in the X-direction is from 5.9s to 11.8s, and in the Y-direction from 5.5s to 11.0s. As shown in the Figures, the shape of each response spectrum tends to follow the design spectrum in the target period range, and, the average spectrum provides a good approximate to the design spectrum.

2.5. Building responses

The building response to each acceleration input motion are determined using the nonlinear dynamic analysis option built in the CANNY (Li, 2015) program. Each CMV input motion predicts a critical displacement demand. To verify this prediction and for illustration purposes, we compare it with the critical demands from direct analysis. The latter requires the following steps (i) the CMV input motion (horizontal ground motion pair) is rotated clockwise at increments of 5º in the range of 0º to 180º, (ii) the building dynamic response is calculated for each rotated ground motion pair and (iii) the maximum value from all peak displacement envelope defines the critical demands.

In the example that follows, the critical displacement demands are obtained for the input motion derived from 1999 Kocaeli earthquake (record NGA1148). To demonstrate the effectiveness of the CMV method to predict the critical displacement demands, a comparison of the critical demands and the demands due to the CMV ground motion appears in Figures 5 and 6.

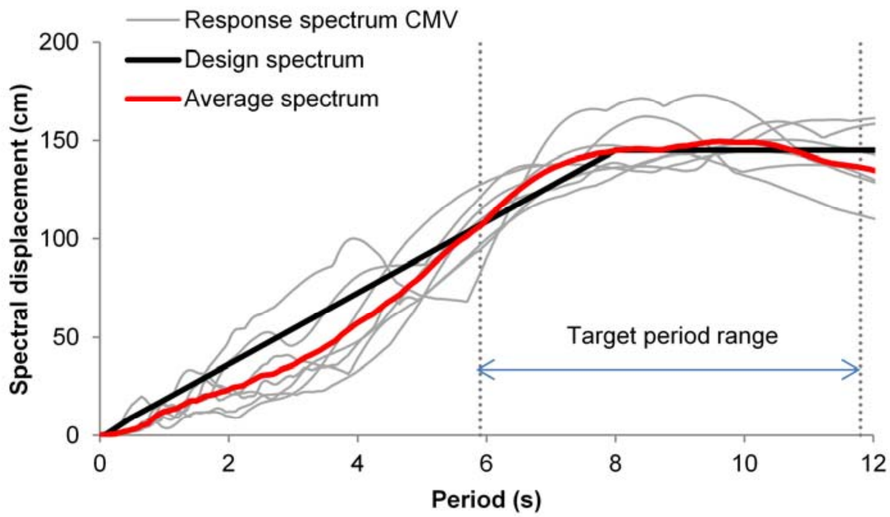


Fig. 3 – Design spectrum and spectra for CMV input motions of suite 1 in the X-direction

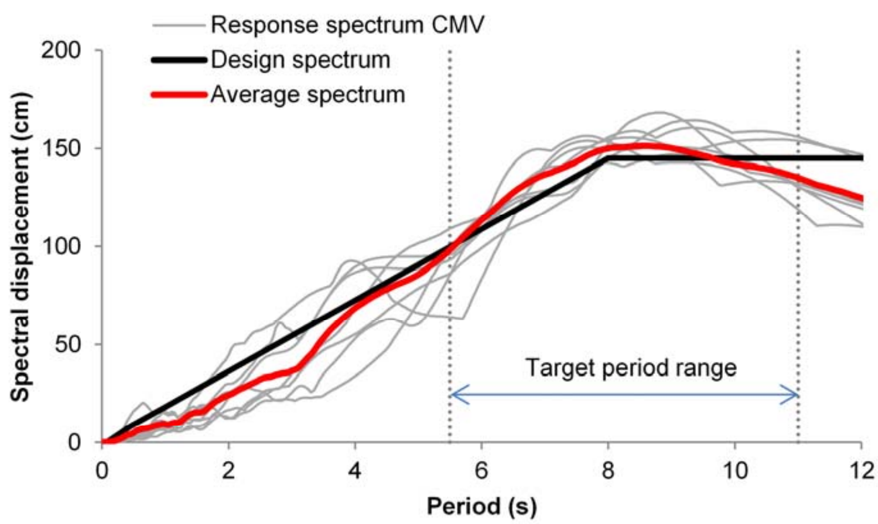
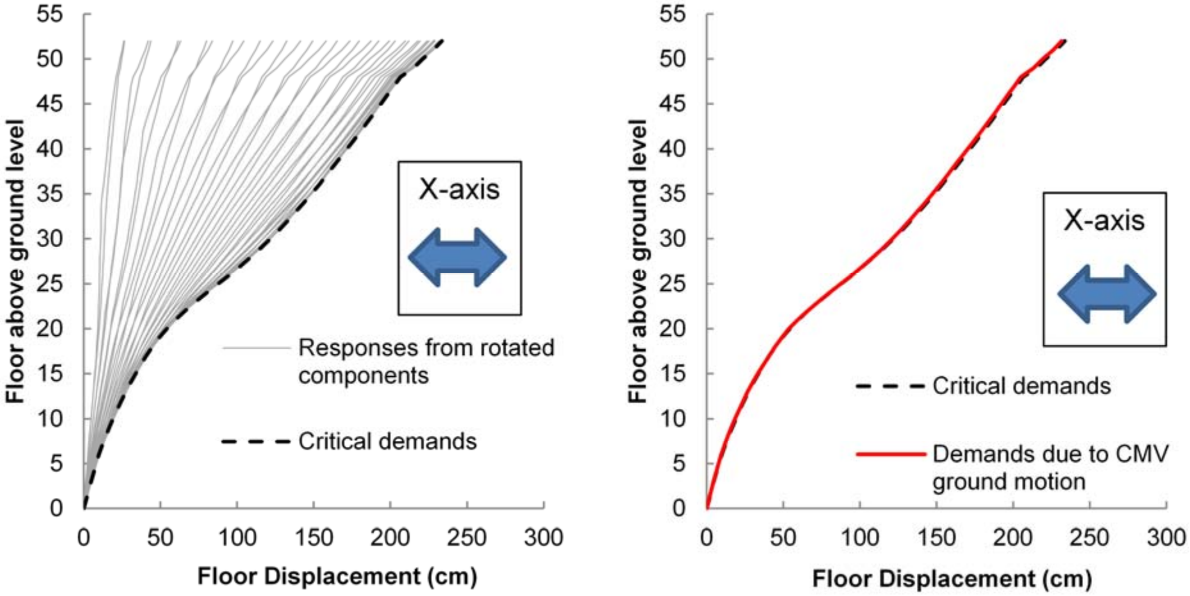


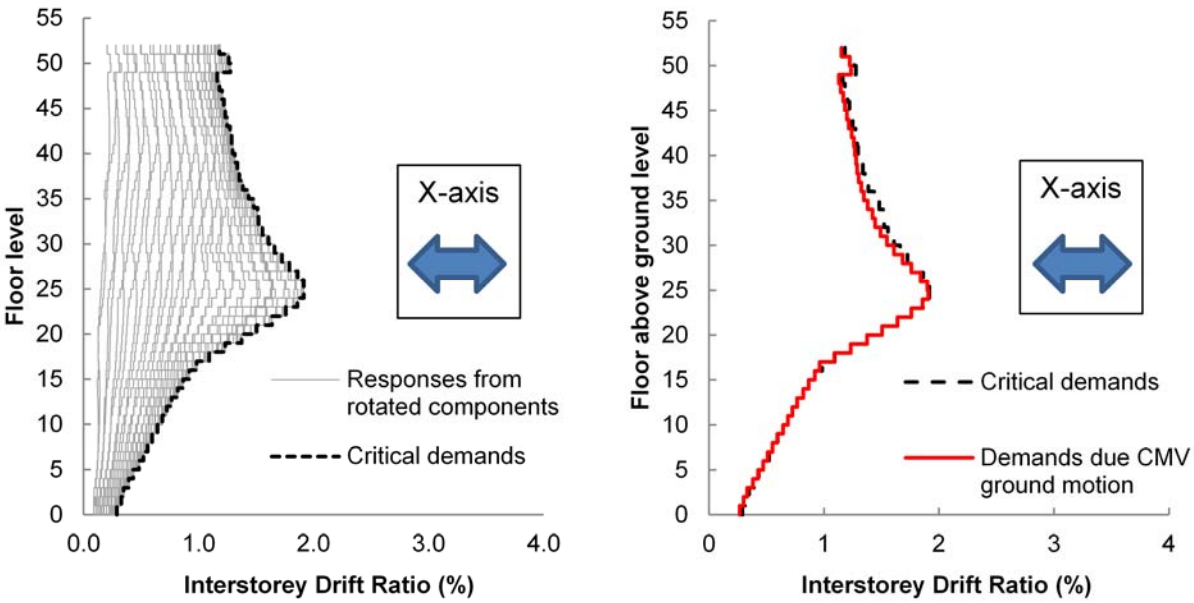
Fig. 4 – Design spectrum and spectra for CMV input motions of suite 2 in the Y-direction

The responses obtained when the ground motion pair applied at multiple angles of incidence appear in the panel (a), and the predicted critical displacement vs direct analysis in panel (b). The prediction of critical floor displacements and interstorey drift ratios (IDR) is remarkably good, with the advantage that a single analysis is performed using the CMV input motion whereas direct analysis requires many more analyses, which is not recommended for performance based design.



(a) Responses for rotated motions every 5° **(b) Critical demands and CMV demands**

Fig. 5 – Prediction of critical displacement demands in the X-direction



(a) Responses for rotated motions every 5° **(b) Critical demands and CMV demands**

Fig. 6 – Prediction of critical interstorey drift ratio demands in the X-direction

Figure 7 shows the critical interstorey drift ratios predicted for each input CMV motion and the respective peak interstorey drift ratio in the orthogonal direction for all the 14 ground motions. Panel (a) shows the IDR in the X-direction and panel (b) in the Y-direction. The profiles in black are obtained when the CMV input motion is applied along the X-axis, and the gray profiles when the CMV input motion is along the Y-axis. In the cases that we analyzed, the pulse-like characteristics of the CMV ground motion produced close estimates of the critical displacement demands in the direction of a given structural axis while small displacements occurred in the orthogonal axis. The median IDR divides clearly the demands that obtained with the CMV along the structural axis from the rest of cases analyzed. Furthermore, Panel (c) and (d) compares the mean and the mean+standard deviation of the IDR from the CMV method and direct analysis, all the rotated ground motions at every 5°. Interestingly, the CMV method using 14 ground motions provides an estimate close to the mean IDR from responses obtained with multiple rotated ground motions. When comparing the mean+standard deviation values, we observe larger differences.

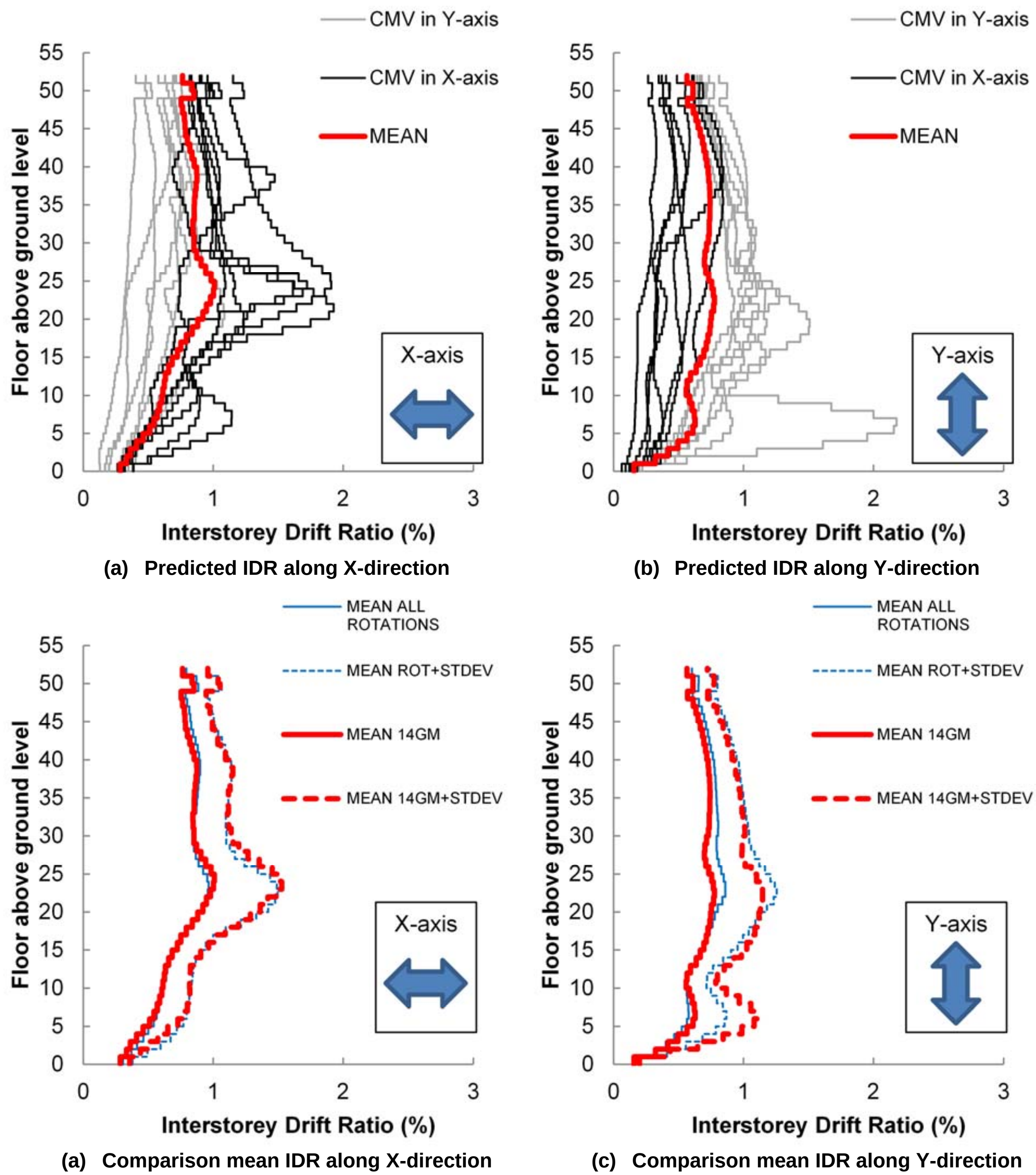


Fig. 8 – Prediction of interstorey drift ratio demands

3. Discussion

This paper presented the CMV method and its application to a case study building. The results demonstrate that although it is an approximate method, it does provide close estimates of the critical displacement demands using a single dynamic analysis. Additional rotations of the ground motion are not required to estimate the critical displacements. If we assume that the critical orientation of the ground motion is random and the process follows a uniform distribution, we observe that the set of selected CMV ground motions did not introduce a bias in the predicted mean demands.

The author’s experience is that selection of ground motions that fit the spectral shape of the target spectrum might become a challenging task, even when the target period range is limited to be from T up to 2T. Recent recommendations for performance based design in Los Angeles allow the alternative of the conditional mean spectrum (CMS) (LATBSDC, 2015). When using this approach, we should develop a multi-scenario spectrum that matches the design spectrum at different periods in the range of T to 2T.

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