Effect of Ground Motion Directionality on Seismic Response of Tall Buildings

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SUMMARY:
Seismic response of a tall building subjected to strong ground shaking depends on the building's structural system and the ground motion characteristics, namely: intensity, frequency content, duration and horizontal ground motion directionality. The latter can be polarized along a narrow range of angles or vary randomly over a wide range of angles. This paper demonstrates the sensitivity of the calculated nonlinear dynamic response of tall buildings to the horizontal ground motion directionality using a case study, a 44 storey reinforced concrete building located in downtown Vancouver, British Columbia, Canada. The building's structural system comprised a core wall, perimeter columns and flat plate slabs. This system is the archetype of modern tall buildings in Vancouver. Numerous nonlinear time history analyses were performed on the structural model using seed pairs of recorded horizontal ground-motion orthogonal components. Records were rotated to forty different horizontal angles of incidence with respect to the building's structural axes in the range of 0 to 360 degrees. The building response estimates show that at critical angle of incidence of the ground motion the floor displacements and interstorey drift ratios could be significantly amplified when compared to response obtained with the as-recorded ground-motion orientation. For each pair of ground motion it was observed that the critical angle of incidence is not unique over the entire building height but over several storey clusters. It was observed that the variation of the response estimates to the angle of incidence of ground motion followed a waveform pattern when the ground motion is strongly polarized. This pattern suggests that ground motions having an angle of incidence close to the critical value will induce large demands in the structure as well. The results of this study show that ground motion directionality is very important for the non-linear analysis of tall buildings, and this has to be taken into account by structural engineers involved in the analysis and design of tall buildings. Possible approaches to deal with ground motion directionality include a preliminary evaluation of the predominant directions of shaking of the ground motion or performing at least two nonlinear analyses rotating the orthogonal components at 0 and 90 degrees with respect to the structural axes of the building model.

Keywords: Ground Motion Directionality, Seismic Response Tall Buildings, Critical Angle of Incidence

1. INTRODUCTION

The nonlinear response history analysis (NRHA) method is currently used by earthquake engineers as a mean to assess the seismic performance of tall buildings under ground shaking scenarios. This method is the most advanced tool that provides the best estimates of structural inelastic response to ground motion. This procedure follows a direct time step-by-step integration scheme of the coupled equations of motions of the multi-degree of freedom model of the building's structure.

The definition of seismic input for NRHA in seismic design of modern tall buildings includes site seismic hazard estimates, selection and scaling of ground motion records representative of the seismic hazard at the site, site response analysis and considering soil structure interaction effects (PEER, 2010). In the conventional seismic input definition for NRHA the influence that the horizontal ground motion directionality has over the building seismic response is not routinely considered.

The input ground motions are typically applied along the structural axes of the building model. These axes are usually perpendicular to each other. Many structural systems have different lateral strength and stiffness along the two orthogonal structural axes. Structures exhibiting dynamic characteristics that are dependent on the orientation they are evaluated usually will have preferred directions of response. Stewart et. al. (2011) recently has coined the term *azimuth-dependent* structures to identify these types of structures. These structures are deemed to be sensitive to the ground motion directionality. Other structures that have same lateral strength and stiffness along all directions and do not have preferred directions of response, e.g. flagpoles and circular tanks, have been named as *azimuth-independent* structures.

This study evaluated the influence of ground motion directionality on the nonlinear dynamic response of tall buildings. The influence of ground motion directionality was evaluated for a case study. The building has 44 storeys, and resembles the general features of the structural configuration commonly provided to modern reinforced concrete tall buildings in Vancouver, British Columbia in Canada. The NRHA method was used to estimate seismic response of the building model to bi-directional ground shaking.

This method was systematically applied to perform analysis at different angles of incidence of the horizontal ground motion components. Horizontal ground motion representative of seismic hazard 2% in 50 years in Vancouver was considered for analyses, due to space limitations the results for one seed pair of ground motions is presented in this paper. The numerous calculations were compared with respect to a reference scenario, which was defined by seismic response of the building model to the ground motion having as recorded orientation (zero degree angle of incidence).

2. RECENT DEVELOPMENTS

Most of the studies published on the response of structures to multi-component earthquake excitation and critical angle of incidence under response spectrum analysis (Menum and Der Kiureghian, 1998; Wilson et. al., 1995) and time history analysis (Lopez et. al., 2000; Athanatopoulou, 2005) are limited to elastic dynamic analysis only. Meanwhile few studies conducted on the effect of ground motion directionality on nonlinear dynamic response are for low-rise and mid-rise buildings (Rigato and Medina, 2007) and (Lagaros, 2010). The study conducted by Rigato showed that for an individual ground motion the ratio of peak responses of the structure model over all angles of incidence to the peak deformation with the as recorded ground motion orientation could be as large as 5.0.

The Council of Tall Buildings recommendations (Willford et. al., 2008) are that seismic input ground motions be applied along the structural (principal) axes of the building model when doing NRHA. A complementary NRHA should follow by applying the same ground motions but rotated 90 degrees. The response envelopes of both analyses are combined to define an overall envelope. This approach attempts to address the influence of ground motion directionality on seismic response of tall buildings.

Huang et. al. (2008) investigated the orientation of maximum spectral demands in the near fault ground motions and compared them to geometric mean spectral demands defined by current Next Generation Attenuation (NGA) relationships (Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008). Using a suite of 147 records obtained from PEER NGA strong motion database an orientation or axis (or small set of axes) along which the maximum spectral demand was attained for several period ranges of the elastic oscillator was found. The ground motions were recorded in events of moment magnitude M_W greater than 6.5 and a source to site distances R_{rup} less than 15km. The study suggested that maximum spectral demands could be obtained by scaling factors to increase the geometric mean spectral demands. It was found that strike normal spectral demands were significantly an unconservative estimate for maximum spectral demands.

Stewart et. al. (2011) raised concerns over the conservatism introduced by defining a design spectrum for maximum direction as currently presented in the 2009 National Earthquake Hazards Reduction Program (NEHRP) *Provisions* and defined after the findings of Huang et. al. (2008). The new maximum direction (MD) spectrum replaces the spectrum definition of geometric mean of spectral acceleration for two orthogonal components. They consider that this concept of MD spectrum is adequate to design structures that have identical dynamic properties in all directions. However buildings, bridges and dams do not exhibit such characteristics. They suggest that MD spectrum provides an overhead in seismic design of structures for a demand that the structure is unlikely to experience.

The current building code provisions in the National Building Code of Canada (NRC, 2010) and International Building Code (ICC, 2006) recognize the random nature of ground motion directionality in determining the seismic input. The provision requires the seismic input to be applied along the critical direction. However no guidance is provided on how to properly account for ground motion directionality when NRHA is conducted.

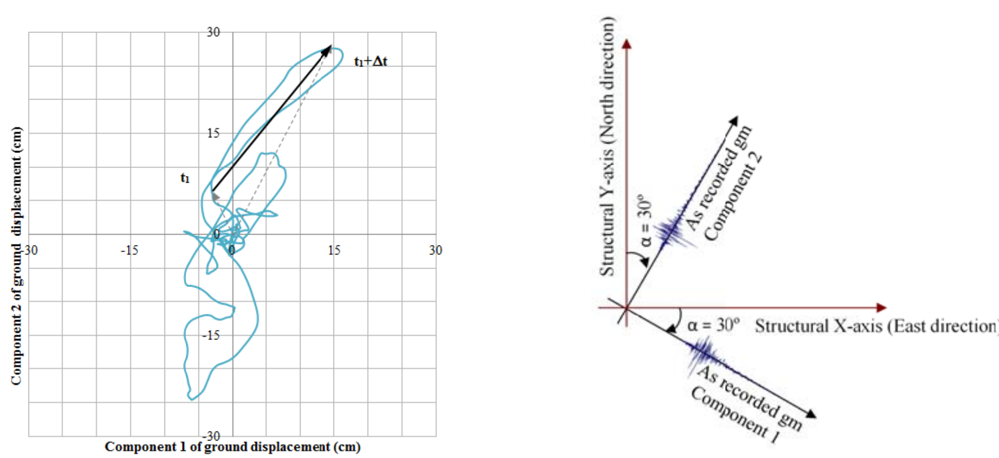
3. DEFINITIONS IN THIS STUDY

3.1. Ground displacement vector: It is defined as the difference between final and initial position vectors of the ground at instant $t_i+\Delta t$ and t_i, respectively. In Figure 1a the horizontal particle orbit for a ground record from the 1989 Loma Prieta Earthquake is presented along with a displacement vector. In this case the initial and final position vectors are shown for a Δt equal to 1 second.

3.2. Directionality of ground motion: It is defined by the direction of the ground displacement vector. In this study the direction is measured counterclockwise with respect to structural X-axis. The directionality of a ground displacement vector represents the angle that the ground motion would have to be rotated clockwise in order for the vector to be aligned parallel to the structural X-axis (East direction).

3.3 Ground motion coordinate system: The horizontal ground motions that are recorded by strong motion instruments have typically two orthogonal components oriented along North (positive) and East (positive), which define a ground motion coordinate system.

3.4. Horizontal ground motion component angle of incidence: When performing time history analysis it is regarded as the angular deflection the record ground motion coordinate system has with respect to the building structural axes X-positive and Y-positive. If the recorded ground motion components were applied with as recorded orientation along X-positive and Y-positive structural axes the angle of incidence would be zero. The angle of incidence is measured clockwise as shown in Figure 1b.



(a) **(b)**

Figure 1. Loma Prieta horizontal particle motion and example of horizontal ground motion angle of incidence.

From the definitions above it follows that ground motion directionality and ground motion component angle of incidence are related. The former represents a variable characteristic of the ground motion over time while the latter is a constant characteristic given by the ground motion component and structural axes. As the angle of incidence of the ground motion component changes the directionality of the ground motion changes with respect to the structural axes too.

4. OBJECTIVES OF STUDY

Overall this paper intends to illustrate through a case study the effects of ground motion directionality on the seismic response of a tall building. The effects are evaluated through the following exercises:

a) Evaluation of the ground motion critical angle of incidence for lateral displacement and interstorey drift ratios.
b) Comparison of the building response estimates at ground motion critical angle of incidence with respect to ground motion having as recorded orientation.
c) Assessment of sensitivity of building response estimates to ground motion angle of incidence.
d) Qualitative assessment of the influence of higher modes in the response of a building when ground motion directionality is accounted for.

5. METHODOLOGY

The methodology that follows was developed to assess the effect of ground motion directionality on the nonlinear seismic response of a reinforced concrete tall building using a seed pair of horizontal ground motion components. The methodology is comprised of several methods and is illustrated in Figure 2.

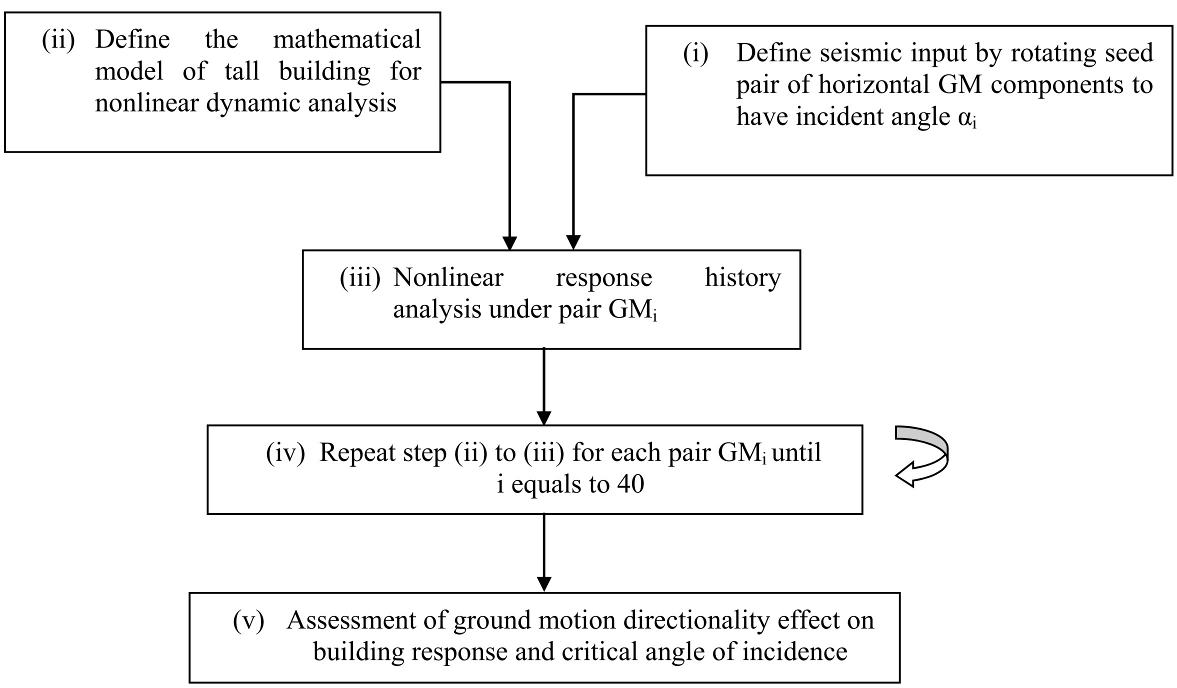


Figure 2. Structure of methodology.

The angles of incidence α_i were selected at a step increment of 10 degrees in the range of 0 to 360 degrees. Supplementary incident angles were included at 45, 135, 225 and 315 degrees.

6. DESCRIPTION OF CASE STUDY

The building used as a reference of this case study is a reinforced concrete 44 storey tower. It was designed in accordance to the National Building Code of Canada 1995. The design of reinforced concrete elements and components was carried out using the CSA A24 (1994).

The building tower is for residential occupancy. It is part of a complex that comprises a residential tower and a hotel tower. The residential tower plan layout is non-symmetrical and the columns are arranged in a non-rectangular grid. The plan average dimensions are 25m and 31m along east-west and north-south. The plan layout distribution in the lower and upper levels is shown in Figure 3.

The residential tower section along east-west and north-south is presented in Figure 3 as well. The residential tower extends 130m above the podium level. The podium structure includes two storey above ground level and 5 underground parking storey. The total height of the podium is 24m from the slab on grade at underground parking level 5 to the floor slab of the level 2. The underground structure height is 15m. The height-to-width ratio of the building is 5 along east-west and 4 along north-south. The building main seismic force resisting system (SFRS) is provided by reinforced concrete core shear walls, and the gravity load resisting system is provided by reinforced concrete columns and shear walls. The slab is part of the SFRS and the gravity load carrying system.

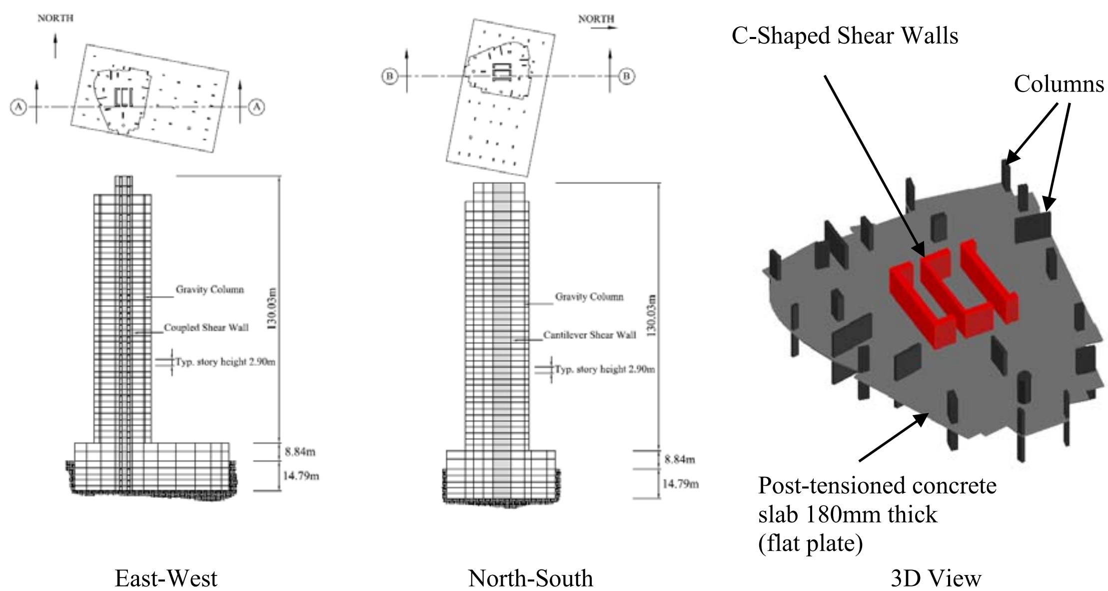


Figure 3. Building plan layouts/sections and 3D view of typical floor layout.

A thorough description of the mathematical building model, the ground motion selection and scaling can be found in the thesis of Archila (2011). The mathematical model was calibrated to a modal model developed through system identification using ambient vibration measurements (Turek et. al., 2007). The gravity loading criteria was taken from NBCC 2010 (NRC, 2010) and ATC-72 (PEER, 2010) for NRHA. The natural periods of the building along east-west direction were 4.27s, 0.96s, 0.44s for the first three modes and 3.75s, 0.85s and 0.35s along north-south.

The seed pair of ground motion records was selected from the suite of records from the Loma Prieta (1989) earthquake in California. This event was magnitude Mw 7.1 with a reverse faulting mechanism at a shallow depth of 18 km. The records were retrieved from the PEER Strong Motion Database (PEER, 2010) and correspond to the CDMG 58065 Saratoga Aloha Ave Station (NGA 0802) located at an epicentral distance of 27 km and site shear wave velocity V_{s30} of 370 m/s.

There are not mapped faults in the proximity of Vancouver City. This precludes the evaluation of a particular direction along which stronger shaking could hit the building. Because of this, in the present case study the as recorded ground motion components were applied along the structural axes of the building. The Loma Prieta motion response spectrum and Fourier spectrum are shown in Figure 4. The respective horizontal particle motion is shown in Figure 1a. The first three natural modes of the building model along east-west are shown with hidden line in Figure 4.

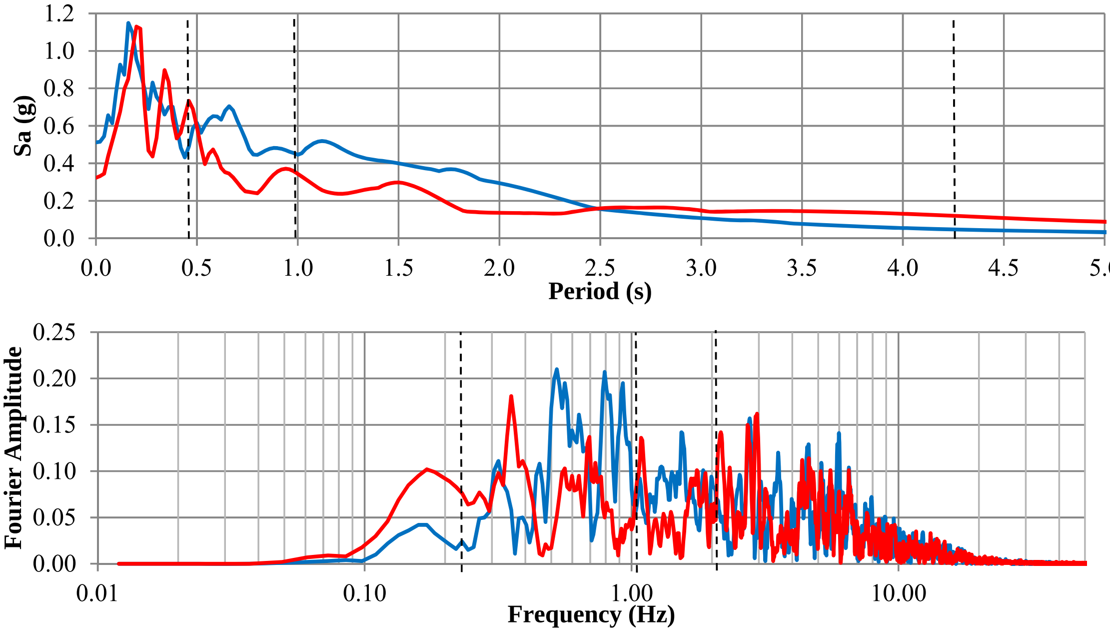


Figure 4. Loma Prieta response spectrum and Fourier spectrum.

7. RESULTS

The nonlinear response history analysis case study results obtained with program CANNY (Li, 2010) are shown in this section. The floor displacement, overturning moment and interstorey drift ratios obtained with the Loma Prieta input motions are presented in detail through Figures 5 to 8. The sensitivity of the displacement response to the ground motion angle of incidence is shown in Figure 9.

The envelopes of floor displacement over the height of the building along East-West direction obtained for the Loma Prieta input motion are shown in Figure 5. The envelopes correspond to 40 scenarios of ground motion angle of incidence, ranging from 0 to 360 degrees. The displacement envelope when the input motion is applied with a horizontal angle of incidence of zero degrees is shown in colour blue, which corresponds to the as recorded orientation. The displacement envelope with the as recorded ground motion rotated at a 90 degrees angle of incidence is shown in red colour. The remaining envelopes in grey colour correspond to other different angles of incidence.

The absolute envelope of the displacement response is shown with a black contour in the left side of Figure 7. Alongside is the critical angle of incidence at each floor level. This absolute envelope is obtained by taking the largest displacement from the outermost profiles in Figure 5, it being the displacement at the critical angle of incidence. The absolute envelope in Figure 7 is compared against the displacement envelope when the ground motion angle of incidence is zero degrees (as recorded orientation), the latter response is shown with a blue line. The ratio of these envelopes is used to define a response amplification factor at each floor level, this factor is depicted by the colour scale.

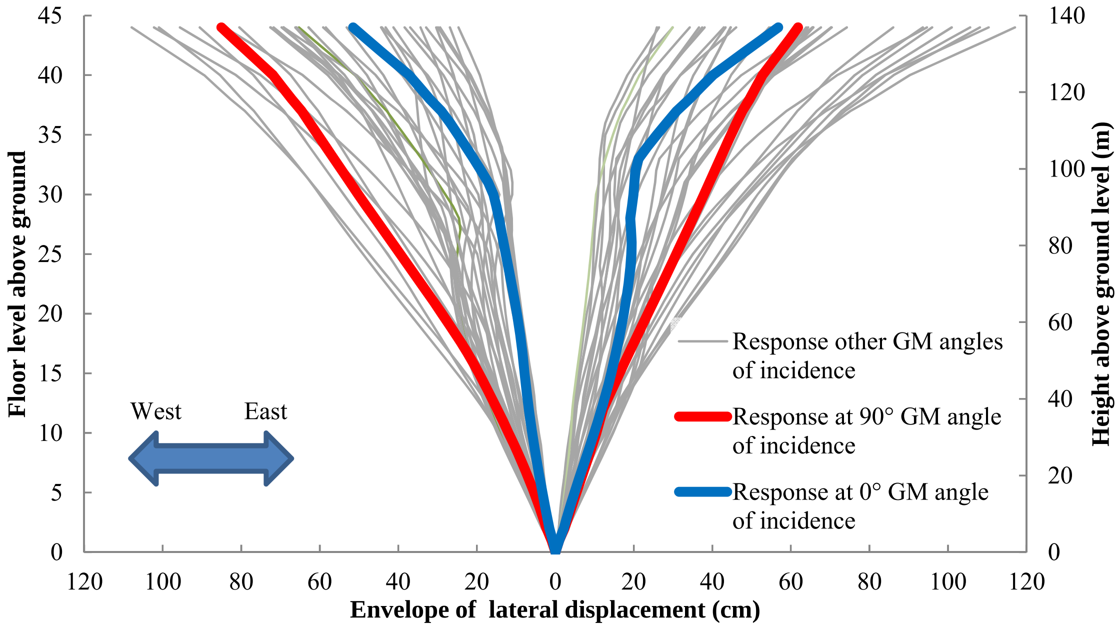


Figure 5. Envelopes of displacement response along east-west direction.

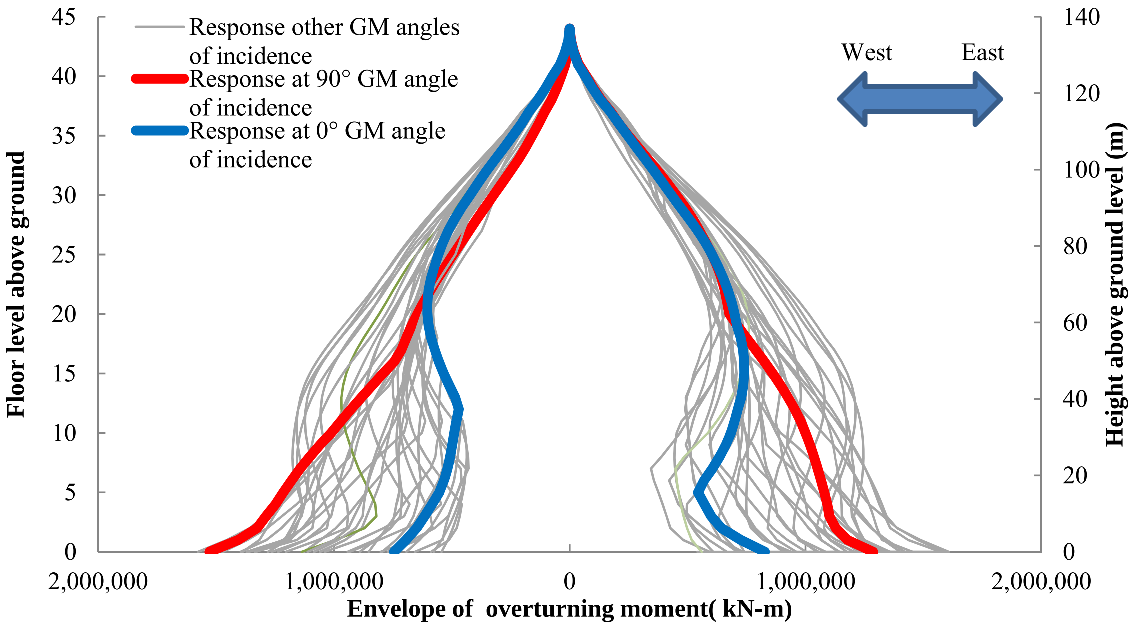


Figure 6. Envelopes of overturning moment along east-west direction.

The displacement amplification factor spanning from ground level up to floor level 18 ranges between 1 and 2. However for the remaining upper floor levels, 19 and above the amplification factor ranges between 2 and 3.5. It is clear that this building model excited by the Loma Prieta ground motion exhibits a displacement response that is more sensitive to the angle of incidence of the ground motion for floor levels 19 and above.

The sensitivity of the floor displacement to the ground motion angle of incidence is presented in Figure 9 along EW and NS directions. The displacements along EW are greater than displacements along NS, this can be expected since a pushover curve showed that the building model has larger stiffness and strength along NS direction.

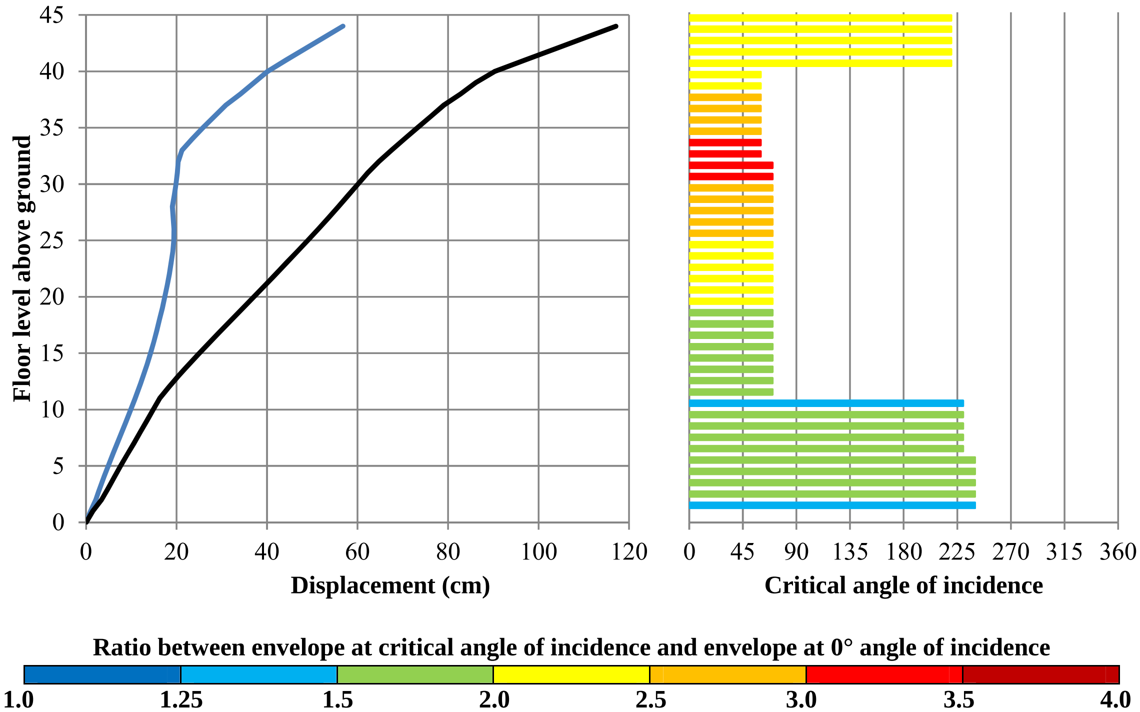


Figure 7. Critical angle of incidence for absolute displacement envelope along east-west direction.

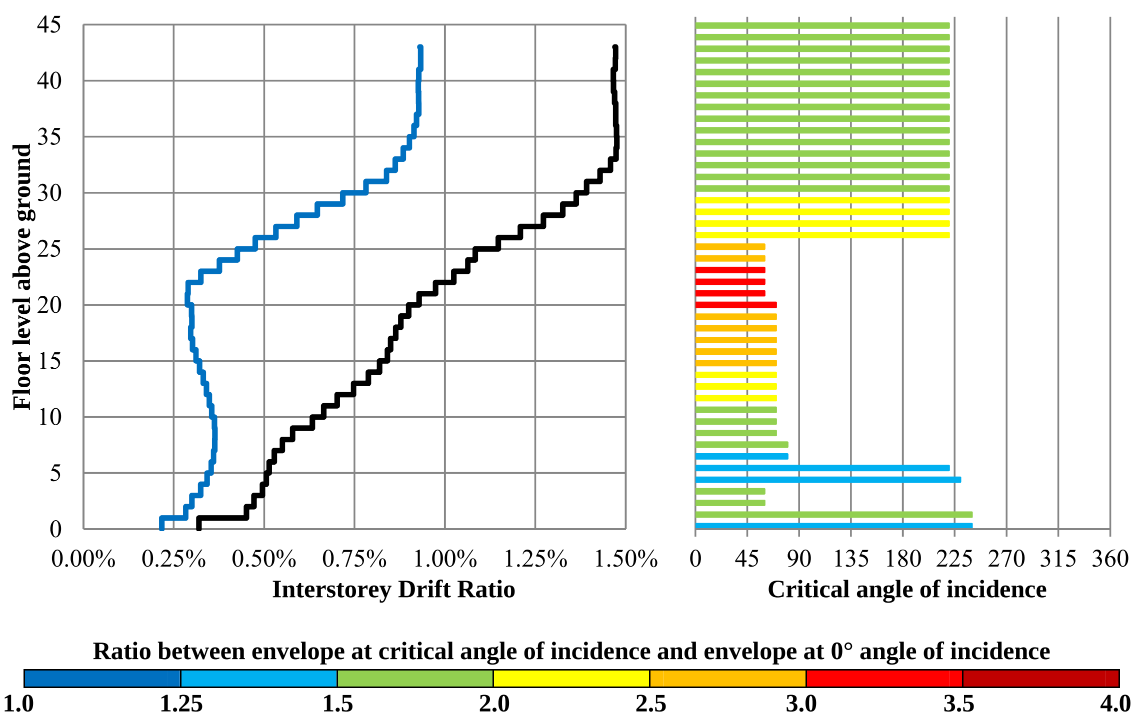


Figure 8. Critical angle of incidence for absolute interstorey drift ratio envelope along east-west direction.

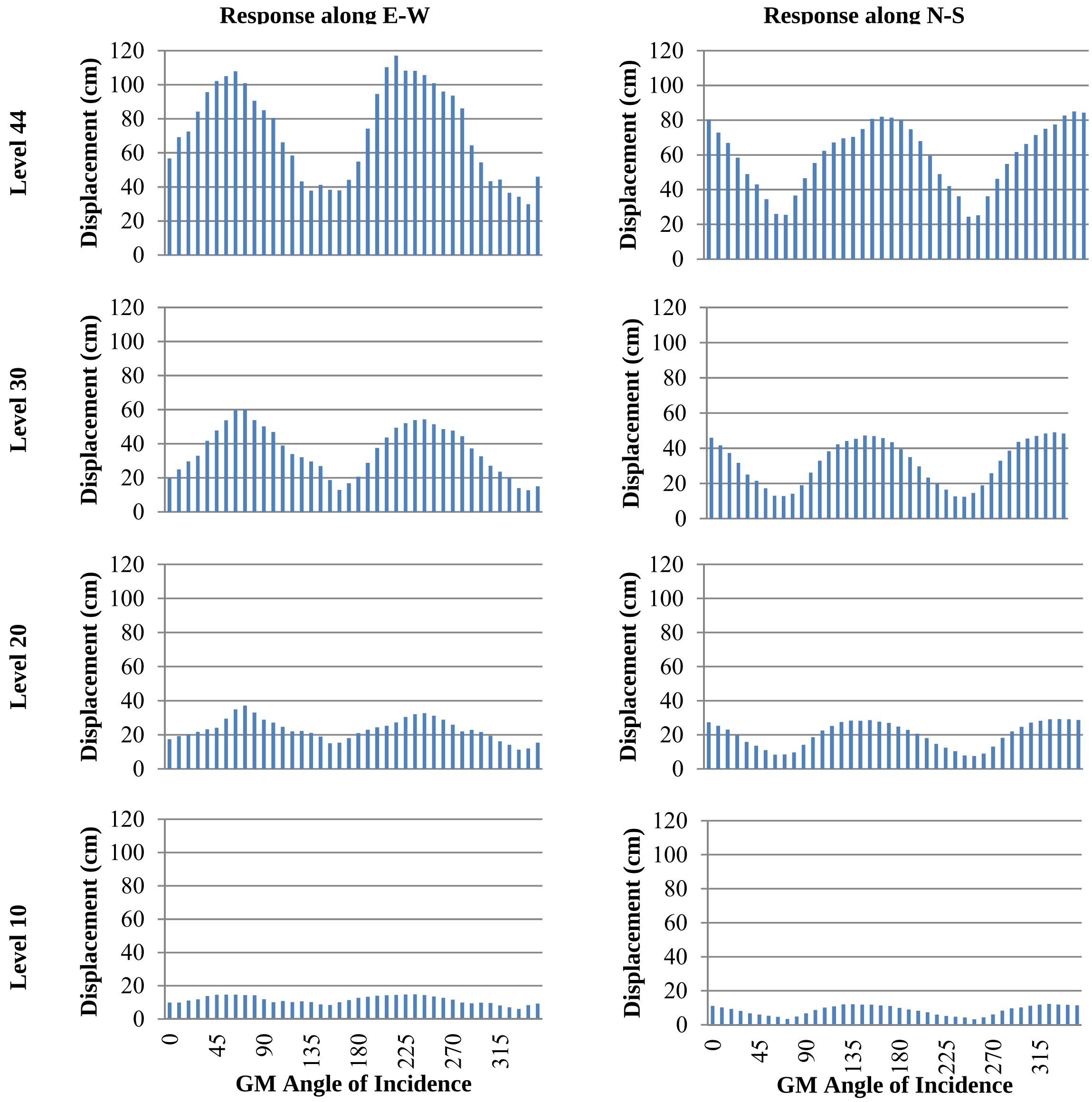


Figure 9. Maximum lateral displacement as a function of the ground motion angle of incidence.

8. DISCUSSION

The Fourier and response spectra for east and north components of input ground motion show clear differences in their frequency content which are reflected in different dynamic responses of the building model along East-West in Figure 5 through 8. The 0 degrees angle of incidence ground motion (east component) has more energy in the low frequencies (0.10-0.35 Hz) than its counterpart; conversely the 90 degrees angle of incidence ground motion (north component) has more energy in the high frequency range (0.50-1.50 Hz). The 0 degrees angle of incidence ground motion would mainly excite the first mode at 0.23 Hz whereas the 90 degree angle of incidence ground motion would mobilize higher modes.

This is confirmed in Figures 5 and 6 by the almost linear profile of the displacement envelope and the corresponding overturning moment under the 0 degrees angle of incidence ground motion, the building model response under the 90 degrees angle of incidence ground motion exhibits a significant participation of higher modes. Therefore the widespread responses in the displacement and the overturning moment envelopes can somehow justified by the differences in the frequency content of the input motions. Additional source of the estimates variability is the model inelastic response.

The critical angle of incidence along east-west at each floor in Figure 7 varies over the building height. This variation suggests that the probability of being excited at a critical angle of incidence is greater for a high rise building than a low rise building; this difference is mainly due to the increased participation of higher modes in the dynamic response of a high rise building.

There are five different critical angles of incidence which cluster many storeys, these critical angles are 60, 70, 220, 230 and 240 degrees. Performing analysis for a higher resolution than 40 ground motion angles of incidence could produce fewer critical angles of incidence. It is possible that the critical angle of incidence for displacement of storeys 11 to 39 is between 60 and 70 degrees, but this is not captured with the 10 degree step resolution used for the case study.

The sensitivity of the building response to the ground motion angle of incidence is expected to follow a wavepattern as shown in Figure 9, when the ground motion is strongly polarized and the building has a regular distribution of strength and stiffness in all directions. A clear trade is observed in the building response, when floor displacement is a minimum in the EW direction the displacement is a maximum in the NS direction and viceversa.

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