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Seismic Performance of Non-Ductile Reinforced Concrete Frames Subjected to Vertical Ground Motion

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ABSTRACT: Poor seismic performance of non-code conforming (non-ductile) reinforced concrete (RC) buildings designed prior to 1970s (for gravity load only), highlights the need for reliable seismic risk assessment and retrofit guidelines. Existing seismic design and performance assessment of buildings considers horizontal component of the ground motion only. However, from recent earthquake reconnaissance reports, it is reported that vertical ground motion can be significant on the performance of the structure depending on the characteristic of the ground motion. Although number of research work was reported to understand the effect of vertical ground motion in the seismic behaviour of bridge piers, still a lot need to be done for RC frame structures. In this paper, the effect of vertical ground motion in seismic performance of non-ductile RC frame buildings is quantified with an eight-story reinforced concrete frame using near-field ground motions. The nonlinear dynamic analysis was carried out using 2-D finite element models developed in OpenSEES finite element software. The seismic response of frame buildings subjected to horizontal only, and combination of horizontal and vertical ground motions was compared in terms of three engineering demand parameters: interstorey drift, permanent deformation and axial force demand in columns. Finally, the recommendations to consider the vertical ground motion in the seismic performance evaluation of RC buildings are given on the basis of the observations.

1 INTRODUCTION

Most building codes state that vertical (V) component of the earthquake is less severe than the horizontal (H) component, the V/H ratio is assumed to be in the range of 1/3 to 2/3 (Bozorgnia et al., 1998). Consequently, the current design and assessment of structures consider horizontal shaking only (e.g. Elwood 2013). However, from analysis of free-field vertical ground motion, Bozorgnia et al. (1998) have shown that the commonly assumed 2/3 value of V/H is non-conservative for near-filed earthquake at the short periods and reduces to less than 2/3 at long periods. The 1994 Northridge and 1995 Hyogo-ken Nanbu earthquakes generated V/H ratios as high as 1.79 and 1.63, respectively. Normally, the vertical component of ground motion has a lower energy content concentrated in a narrow and high frequency band. This can cause damage to structures having vertical periods within this range (Collier and Elnashai, 2001).

Damage due to high level of vertical acceleration was observed during 1994 Northridge earthquake (EERI, 1995). Brittle failure modes were reported as a result of direct compression or by reduction in shear capacity and ductility due to variation in axial forces. Over two times more vertical acceleration amplification was recorded in buildings during Hyogo-ken Nanbu earthquake (AIJ, 1995). Elwood (2013) has reported very high vertical acceleration during 22 February 2011 Christchurch earthquake, but the damage observed were attributed to horizontal shaking. However, impact of vertical acceleration on the horizontal acceleration is not quantified. Limited number of research works, on the effect of vertical ground motion on structures, has been reported in the literatures. Anderson and Bertero (1973) analysed the response of ten storey unbraced steel frame subjected to both horizontal and vertical components of earthquake and reported increase in the ductility demand of lower and upper storey columns and upper storey girders. Agbabian et al. (1994) experimentally investigated the shear capacity of RC beam-column connections with varying axial load. They reported that the failure mode is a shear failure of the panel zone, however, the significant differences were observed in shear deformation capacity, yield point, cracking pattern, ultimate capacity and ductility of the panel zone.

In this paper, the effect of near-field vertical ground motions in seismic performance is quantified with an 8-story non-ductile reinforced concrete (RC) building. The nonlinear dynamic analysis was carried out using 2-D finite element models developed in OpenSEES finite element software. The seismic response of frame buildings subjected to horizontal, and both horizontal and vertical ground motions was compared in terms three engineering demand parameters: interstorey drift, permanent deformation and axial force demand in columns.

2 BUILDING CONSIDERATION

In order to study the effect of vertical acceleration in seismic performance of buildings, an 8-story non-ductile RC frame shown in Figure 1 is employed. The frame is designed according to an “old” seismic code (i.e., conventional equivalent static forces and no beam-to-column capacity design requirements). The frame elements are modelled in OpenSEES using lumped plasticity, beam with hinge elements. This element is assigned with appropriate fibre section depending on the dimension of the beam and column sections and the location of reinforcement. The concrete behaviour is modelled using Kent-Scott-Park concrete material with degrading linear un-loading/re-loading stiffness and no tensile strength (Scott et al., 1982) while the steel is modelled using Menegotto-Pinto steel material with isotropic strain-hardening (Menegotto and Pinto, 1973). More detail about the building and modelling can be found in Rajeev (2007) and Rajeev et al. (2008).

The small-amplitude first-mode period is computed to be 1.41 second. Mass-proportional damping is assumed and equal to 5% of critical damping at the fundamental mode of vibration.

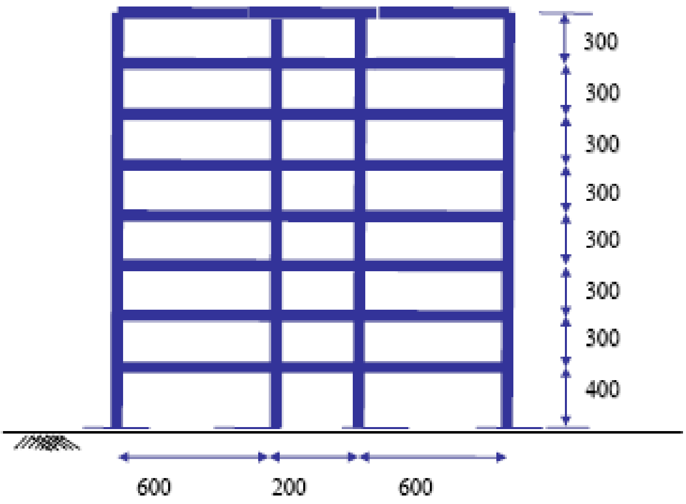


Figure 1. Configuration of case study structure (dimension in cm)

3 GROUND MOTION RECORD SELECTION

The nonlinear dynamic analyses are performed using a set of five real near-field ground motion records. Each record has three acceleration time histories (i.e., two horizontal *X* and *Y*, and one vertical *Z* components). The numerical model of the frame is 2D, therefore, during the analysis, the two horizontal components are combined separately with the vertical component, i.e. $X + Z$ and $Y + Z$). This leads to a total of ten nonlinear time history analyses for combined horizontal and vertical accelerations. In order to quantify the effect of vertical acceleration in seismic performance, an additional ten nonlinear time history analyses are performed only with the horizontal acceleration, i.e. *X* and *Y* components only.

The ground motions were recorded in Soil type C. The moment magnitude varies between 6.3 to 6.7 and the distance varies between 5 to 9 km. The acceleration response spectrum of the records is shown in Figure 2. The V/H ratios at first mode period are shown in the figure. The V/H ratios values range from 0.1 to 1.13, which represents a fairly uniform distribution of week to very strong vertical ground shaking. Further, the vertical to horizontal acceleration ratios are computed for period up to 4 s and shown in Figure 2 (last). The assumption of 2/3 value of V/H in design of structure is not valid across all the periods. The V/H ratio reaches up to 10 at 0.1 s and 2 at 0.5 s.

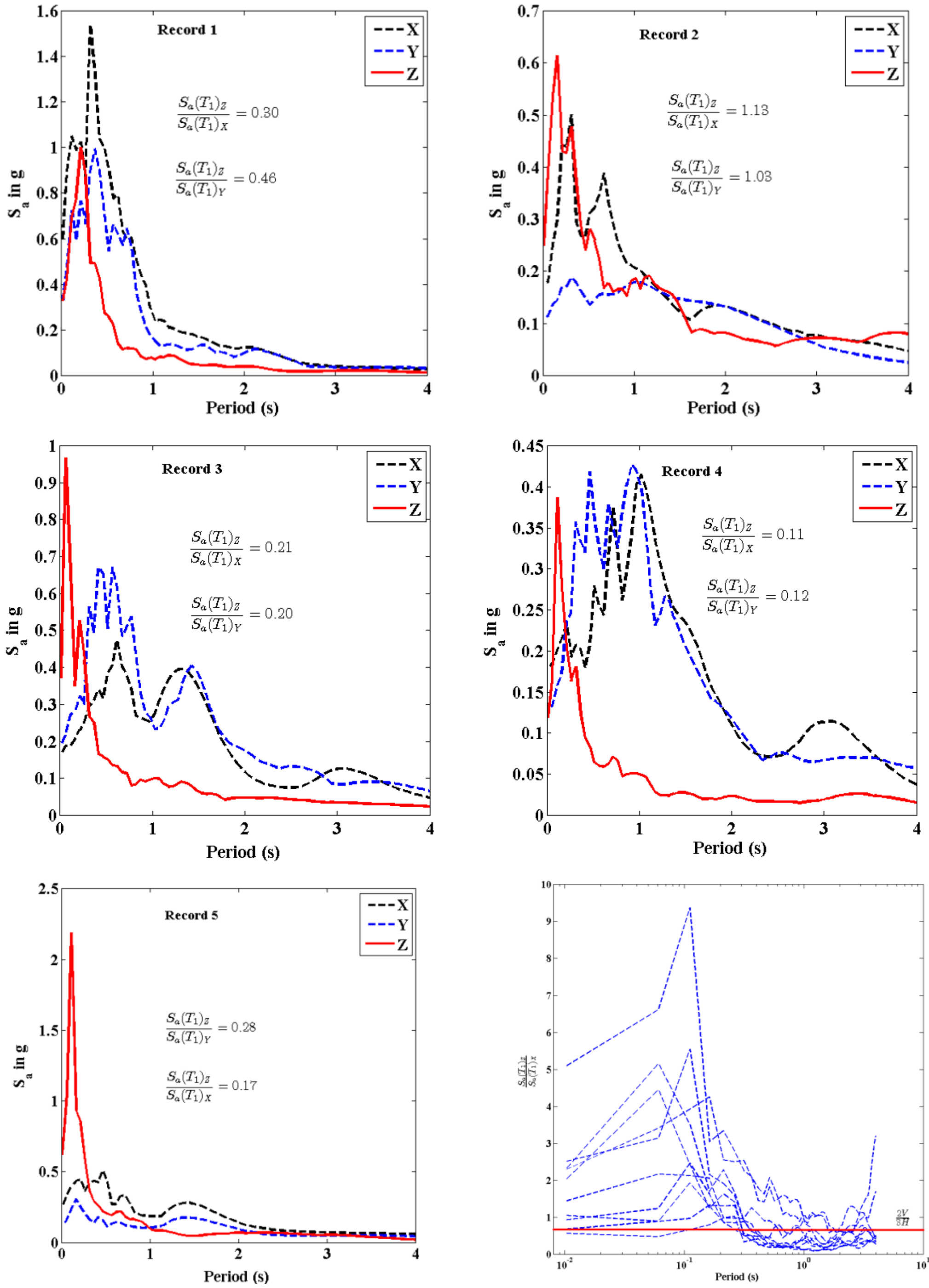


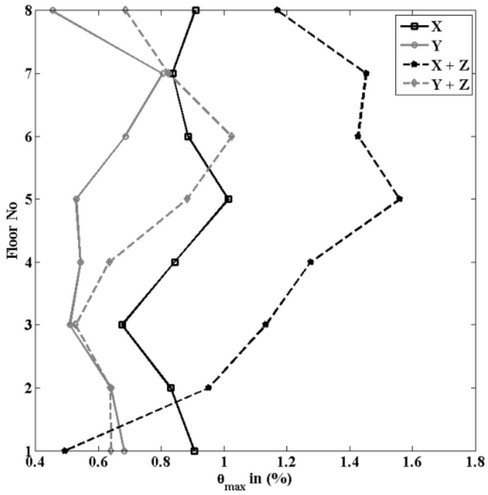
Figure 2. Acceleration response spectrum of selected ground motion and the vertical to horizontal spectral acceleration

4 RESULTS AND DISCUSSION

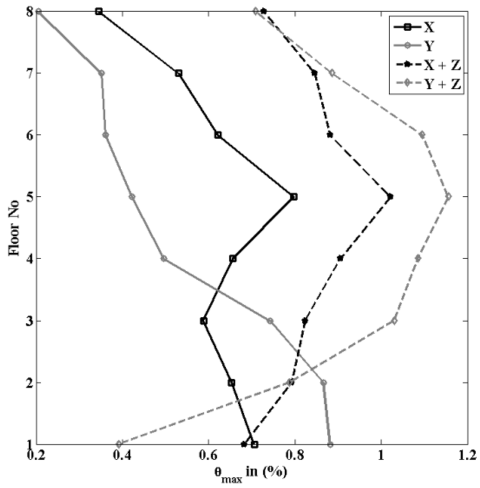
Nonlinear dynamic analysis is performed with the real ground motion records discussed above. The structural responses are determined in terms of maximum interstorey drift ratio (θ_{max}), permanent deformation of top floor at the end of the shaking and axial force demand in columns.

4.1 **Interstorey drift**

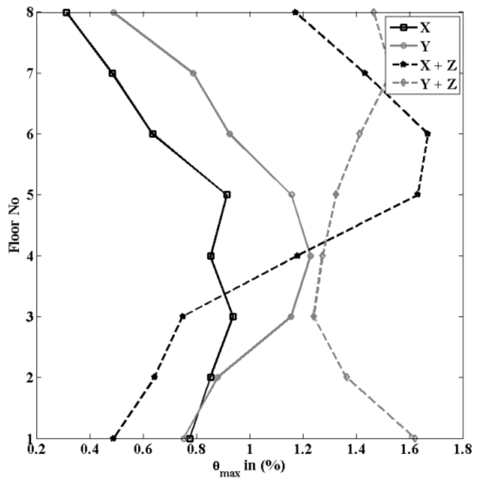
The θ_{max} value is computed for each floor and simulation. Figure (3) shows the θ_{max} values for all the records. In general, for most records (Figures 3a, b, c, e), the θ_{max} is significantly higher in combined horizontal and vertical shaking (i.e. $X + Z$ and $Y + Z$) than the horizontal shaking only (i.e. X and Y). Record no 4 (Figures 3d), however, the ratio between the spectral acceleration at first mode period of vertical and horizontal component is very low (i.e., 0.11 & 0.12). Further, the θ_{max} of the first floor decreased while the θ_{max} for the rest of the storeys increased for combined horizontal and vertical shaking.



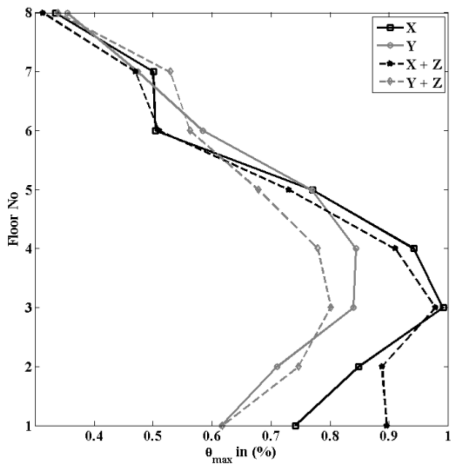
(a)



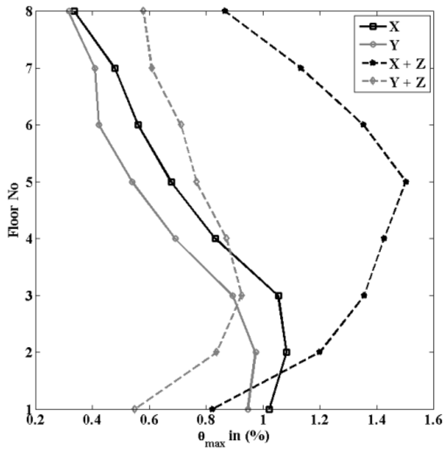
(b)



(c)



(d)



(e)

Figure 3. Maximum interstroey drift envelope: (a) to (e) correspond to records (1) to (5)

Figure 4 shows the ratio of the maximum interstorey drift of combined shaking ($\theta_{\max}^{HV}$) and the maximum interstorey drift of horizontal shaking ($\theta_{\max}^{H}$) against the ratio of spectral acceleration of vertical and horizontal shaking at the first mode period. No clear relationship/pattern can be discerned from the results. The drift values increases by 20 to 80% when the vertical spectral acceleration is above 20% of the horizontal, and below 20% the effect of vertical acceleration is not significant.

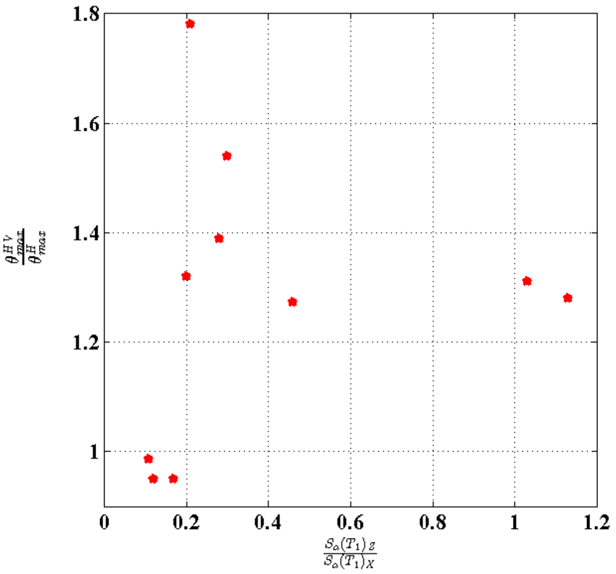


Figure 4. Ratio of maximum interstroey drift for the combined shaking and horizontal shaking Vs the ratio of spectral acceleration in vertical and horizontal directions at first mode period

4.2 Permanent deformation

The permanent deformation of the top storey is computed at the end of the analysis and compared the horizontal and combined shanking. Figure 5 shows the comparison of permanent deformation computed for records 1 and 2. There are significant different (i.e., 100 to 200 mm) in permanent deformation for the combined shaking than the horizontal shaking. This may be due to the increase in overturning moment (i.e., P-Δ) caused by large axial forces.

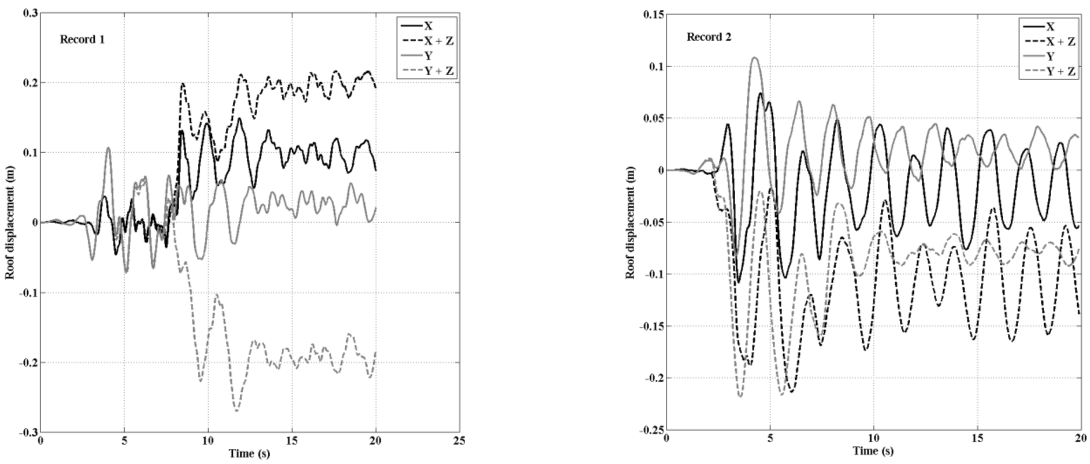


Figure 5. Displacement time history of top floor

4.3 Axial force demand

The axial force envelop for all columns in the frame is determined and compared with the gravity load on the respective columns. Figures 6 top and bottom shows, respectively, for record 1, the axial force envelops of all the columns for horizontal and combined shaking together with the normalised axial force percentage. The normalised axial force is computed using the ratio between the maximum compressive force in the column and the compressive capacity of the respective column. The compressive force increases and reaches 60% of the capacity for the combined shaking while up to 35% increase can be found for the horizontal shaking.

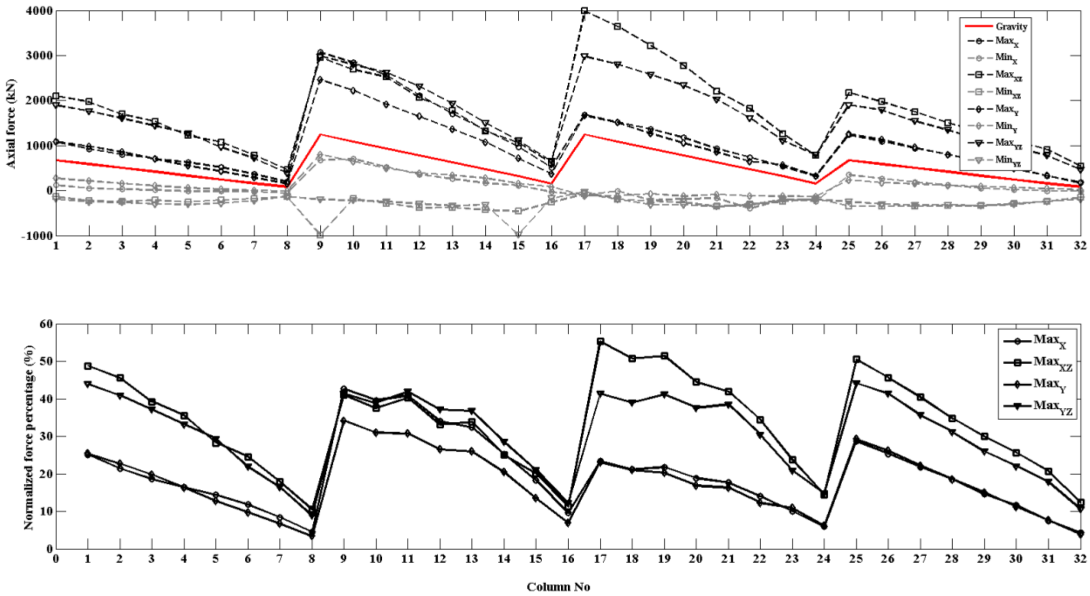


Figure 6. Axial force envelop of all the columns (Top) and the normalised axial force percentage (Bottom) for record 1 [To read the figure column No 1 to 8 is exterior columns on the left from bottom to top, column No 9 to 16 is the interior columns on the left from bottom to top, column No 17 to 24 is the interior columns on the right from bottom to top, and column No 17 to 24 is the exterior columns on the right from bottom to top]

5 SUMMARY AND CONCLUSION

This paper presents the effect of vertical ground motion on the seismic performance of non-ductile RC frame structures. The frame represents low to medium rise buildings built prior to 1970 in Eastern Europe. The nonlinear dynamic analysis is performed using five near-field ground motion records. The following observations are made based on this study:

(1) The interstorey drift demand increases by up to 80% for the combined vertical and horizontal shaking in comparison to the horizontal shaking. The increase in drift demand is not significant for the records having vertical to horizontal spectral acceleration ratio at the first mode period below 0.20. Further the increase in drift demand is based on the characteristic of the records (i.e., duration and frequency content, etc.).

(2) The permanent deformation at the top of the structure increases considerably.

(3) The axial compressive force increases close to 50% of the compressive forces capacity of the columns. Further, the significant amount of tensile forces (> 1000 kN) developed during shaking.

On the basis of the above observations, the vertical ground motion should be considered during the design and assessment of structures via nonlinear time history analysis. The current design approach of taking 2/3 of horizontal acceleration as the vertical component may not lead to a safer design. However the above findings need further studies with different height and type of buildings and consideration of more near-field records to draw a solid conclusion and make a design recommendation.

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