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NEAR-FIELD EFFECTS ON TALL STRUCTURES

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ABSTRACT

Near-field records are rich in high frequencies because of the short travel distance of the seismic waves. In addition, in the forward directivity zone, the near-field records may contain large amplitude velocity pulse, often of significant duration. Consequently, due to these characteristics these records are susceptible to create an unexpected response on long period structures.

The objective of this study is to characterize the effects of the near-fault records on tall structures where the structural periods are long and the effects of the higher modes are prominent. In order to achieve this, two case-study structures, one 20-storey and another 30-storey, designed according to the Direct Displacement Based Design Procedure, have been analysed. Natural ground motion records are used for the analyses. The records have been grouped according to R, the epicentral distance, being varied among 0-7.5 km, 7.5-15 km, 15-25 km, 25-35 km and 35-50 km in 5 different bins. The analyses have been conducted in OpenSees (2013) where fibre-based distributed-plasticity elements are employed.

The results of the analyses have been given in the PEER PBEE format, where an Engineering Demand Parameter (EDP) is compared with an Intensity Measure (IM). The trends of the cloud analyses performed have been obtained for each distance bin. This comparison allows engineers to have a certain relationship, together with an associated level of uncertainty, between the demand and the response. In this study, the spectral acceleration at the fundamental period of the structure, a parameter often used in design, is correlated to the maximum inter-storey drift demand. The results suggest that there is a need to increase the spectral demand for design, as also reported by several other researchers. Such an increase can be effectuated by simply amplifying the design spectrum with a single value coefficient at the long period range. The estimated increased spectral values can 2.0-2.5 times higher than the initial ones. Additionally, it was observed that the effects of the bin with records from 0-7.5 km distance are more pronounced in terms of drift demands, while the records in the 7.5-15.0 km bin were not much representative of the near-fault effects.

INTRODUCTION

Near-fault ground motions are different from ordinary ground motions in that they often contain strong coherent dynamic long period pulses and permanent ground displacements. The dynamic motions are dominated by a large long period pulse of motion that occurs on the horizontal component perpendicular to the strike of the fault, caused by rupture directivity effects. Near fault recordings from recent earthquakes indicate that this pulse is a narrow band pulse the period of which increases with magnitude, as expected from theory. This magnitude dependence of the pulse period causes the response spectrum to have a peak the period of which increases with magnitude, such that the near-fault ground motions from moderate magnitude earthquakes may exceed those of larger earthquakes at intermediate periods around 1 second (Somerville, 2002).

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As a consequence, structures exposed to near-field forward directivity effects may need higher base-shear strength as compared to structures not in such proximity to the source. The attempt to incorporate near-fault effects via increased requirements is reflected to some codes mostly developed after 1994 Northridge earthquake. For example, UBC 1997 includes a near-fault factor of 1.5. Still, as Somerville et al. (1996) note, the shape of the UBC spectrum should be broadened to longer periods to accommodate fault-normal motions originated from forward directivity. Change of the design spectrum was also proposed by Iwan (1997) who alternatively suggested the use of a shear beam in calculating the SDOF response to seismic excitations as a more accurate modelling solution compared to classic SDOF models with elastic beam when near-field response is expected. He strongly supported the use of elastic drift spectra proposed in design procedures.

The inadequacy of the design spectrum in representing near-fault effects has directed research towards the modification of empirical strong ground motion attenuation relations in order to include such phenomena (Somerville et al., 1997) and the attempt to develop appropriate design spectra (eg. eg. Longjun et al., 2006; Maniatakis and Spyrakos, 2011), as well as to the development of near-fault ground motions appropriate for design verification analyses (eg. Somerville et al., 1996) and the analytical simulation of their characteristics (e.g. eg. Pitarka et al., 2000; Mavroeidis and Papageorgiou, 2003).

Within the displacement-based approach proposed by Priestley et al. (2007), for sites exposed to the effects by forward directivity pulses the near-fault effects it is suggested that a modified damping spectra modifier. The reduced spectral coefficient of the damping modifier, tentatively proposed due to limited data, mitigates the effect of damping ratio and results in increased spectral values for a given period as compared to "normal' conditions.

Near-fault records with forward directivity pulses are expected to impose increased demands in terms of displacement and velocity, and acceleration at longer periods, essentially widening the acceleration-sensitive region of the spectrum (Hall et al., 1995; MacRae et al., 2001; Krawinkler et al. 2003, Tothong and Cornell, 2008; Huang et al., 2008). The ratio of the pulse period in the ground motion velocity time-history to the fundamental period has a critical effect on structural response. In particular in tall buildings that are characterised by an initial long period, which will further elongate with inelasticity, the pulse period may coincide with higher modes and cause a travelling wave effect over the height of the building, resulting in large displacements and shear force demands in the upper stories (Champion and Liel, 2012).

Indicatively, in the study by Anderson et al. (1987) a 10-storey steel frame was designed according to the codes and was subjected to representative ground motions recorded during the 1979 Imperial Valley Earthquake. As reported, structures similar to that shown in the paper are sensitive to pulse-like responses where the relative period of the strong acceleration pulse to the fundamental period of the structure is the key parameter. Malhotra (1999) presented a simple interpretation of the response characteristics of three recorded and one synthetic near-field ground motions, concluding that the pulse-like ground motions tend to exhibit high PGV/PGA ratio, which dramatically influences the response characteristics of the record on structures.

As the idea of a performance-based approach is embraced nowadays, probabilistic seismic hazard assessment is an essential step to be taken before design. Disaggregation will show whether near-fault scenarios dominate and accordingly representative number of near-source records should be included in the record selection, the characteristics of which should be reflected on the final uniform hazard spectrum.

CASE STUDY STRUCTURES AND THE ANALYSES CONDUCTED

Two case study structures have been used in analyses in this paper. Both structures were designed with RC shear walls around the perimeter, symmetrically placed, as shown in Figure 1. The most of the lateral load demand is carried by the RC walls in this system while the columns are contributing to bear the gravity loads mostly. The key parameters of the designed structures can be found in Table 1. A simplification is made in modelling where a single RC wall of the structure is modelled with the tributary mass and seismic weight. The details of the walls modelled are shown in Table 2 and Figure 2.

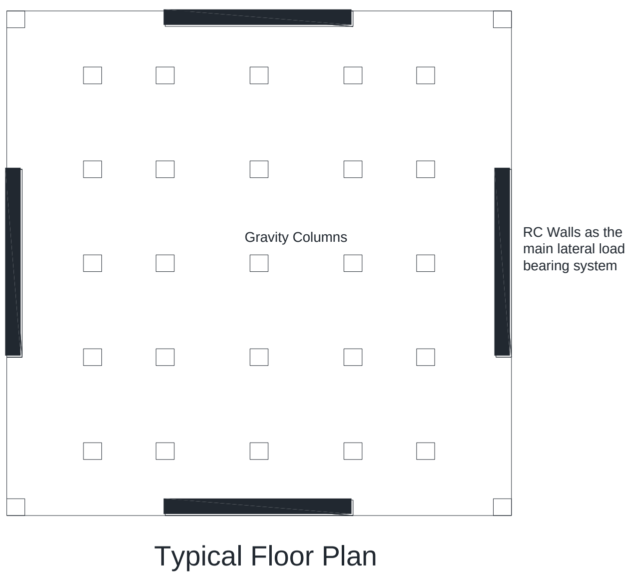

Figure 1. Typical floor plan of the case study structures used in analyses

Table 1. Key parameters of the designed case study wall structures

Parameter	Case Study #1	Case Study #2
# of storeys	20	30
Storey height (m)	3.2	3.2
Tributary storey mass (tonnes)	100	100
RC Wall Length (m)	5	8
Fundamental Period (sec)	3.4	3.2

The analyses have been conducted by using OpenSees software (2013). The walls have been modelled by using 1D frame elements with force-based formulation. The walls are assumed to be designed properly against shear actions, thus only flexural response is taken into account in the fiber models created.

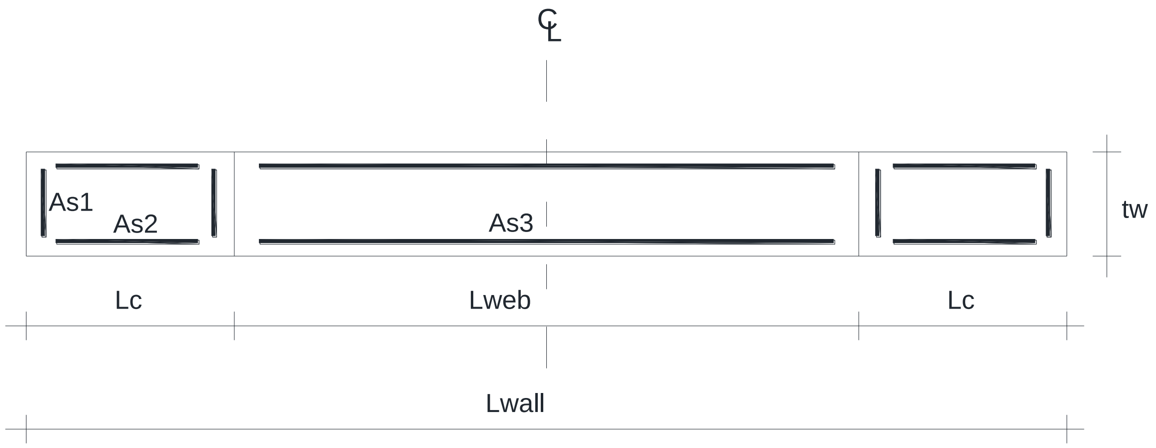

Figure 2. Schematic representation of the RC wall section used for analyses

Concrete quality of the structures designed is C40 while the reinforcing steel is S420 MPa. The head columns have 20% length of the wall section within the first critical floors (1/6th of the total height of the structure) and the width of the head columns decrease to 10% of the wall section length in the rest of the floors. The head columns have concentrated reinforcement of 2-2.5% ratio. The design inter-storey drift was 3%.

Table 2. Structural details of the walls used to represent the two case studies

Structure	Lc (m)	Lweb (m)	Lwall (m)	tw (m)	As1	As2	As3
20-storey	1.0	3.0	5.0	0.5	5ϕ25	5ϕ25	ϕ16/25
30-storey	1.6	4.8	8.0	0.8	8ϕ25	8ϕ25	ϕ16/25

The Mander model (1988) is used for modelling the confinement effects on concrete, while the reinforcement steel is modelled by using Menegetto-Pinto model (1973). The wall section is discretised with fibres of 1.5x1.5cm dimension. A tangent-stiffness Rayleigh damping is used for modelling damping simply because it is the commonest modelling option to which designers resortdue to familiarity, though, more appropriate modelling choices should be made as suggested by Smyrou et al. (2011). The mass is lumped at each storey level. The base of the walls is assumed fixed, neglecting thus the interaction with the foundation and soil.

The natural accelerograms used in the analyses have been taken from PEER NGA database. In order not to couple the effects of different rupture mechanisms with the presented results, only records originated from strike-slip rupture mechanism are accepted in the selection criteria. The soil type is assumed as C class per NEHRP soil classification. Epicentral distance is used in distance calculation mostly because of the availability of this metric parameter for almost all the records in the database.

The case-study structures have been designed according to the direct displacement-based design procedure (Priestley et al., 2007) that has been developed in rather complete form for several categories of structures. In its essence, the method connects structural limit states with global behaviour and the associated level of damage representing the structure as an equivalent single-degree-of-freedom structure with equivalent characteristics. Nevertheless, another design method or code could be alternatively used, since it is deemed that with respect to the purpose of this study the design procedure characteristics are not to play a decisive role on the simple case-studies examined.

The analyses are conducted in “cloud analyses” format, where several acceleration suits, without checking whether they match the pre-defined target spectrum or not, are selected by using some rather lax criteria. The selected records are then applied to the structure without using any scale factor. In this type of analysis, the results should be presented in a continuous form where relating the intensity measure to an engineering demand parameter is possible. The PEER probabilistic approach is followed for this purpose. The spectral acceleration at the fundamental period of the structure is used as the Intensity Measure because of its importance within the force-based design procedure. Spectral displacement could also be employed for this purpose, also for reasons of consistency with the displacement-based design procedure. However, the trend would not change since the spectral acceleration is simply divided with a constant scalar value, i.e. the angular frequency corresponding the fundamental period of the structure. The results are presented both for top displacement and inter-storey drift formats (Figure 3 to Figure 6).

Assessing the response and the trends it exhibits, the use of top-displacement as Engineering Demand Parameter provides different results from the plots produced using the inter-storey drift ratios (Figure 4 and Figure 6). The former is not realistic for tall structures due to the fact that top displacement does not offer any insight into the higher-mode effects. The results, though, are rather interesting, because the top displacement demand appears considerably increased in the case of records with an epicentral distance of 7.5 to 15.0 km. This can be attributed to the fact that the group of records from epicentral distance 7.5 to 15.0 km imposes excitation of different modes in the structure resulting thus in higher top displacements compared to the other cases, but still in lower or equal drift ratios.

Due to the flexible nature of the structures, none of the selected records pushed the structure until the design inter-storey drift limit ratio of 3%. This could be achieved by scaling the records up but the author preferred not to change the energy content and pulse characteristics of the natural records. Thus, the maximum drift ratio obtained in the designed structures remains in the order of 2.0-2.2 %. The trends obtained in Figure 4 and Figure 6, nevertheless, can provide information about the case of 3 % inter-storey drift. The trend-lines have the basic format given in Equation (1). The coefficients of the trend-line equations are given in Table 3.

$$\text{Max Inter-storey Drift (\%)} = (a) \;\; x \;\; [\, Sa(T_1) \text{ in m/sec}^2 \,] \qquad (1)$$

Table 3. IM- EDP relationships for different epicentral distances for the two case-study structures

Case Study	a: Slope of the trend-line for R<7.5km	a: Slope of the trend-line for R>35km
20-storey	2.41	1.61
30-storey	1.40	1.03

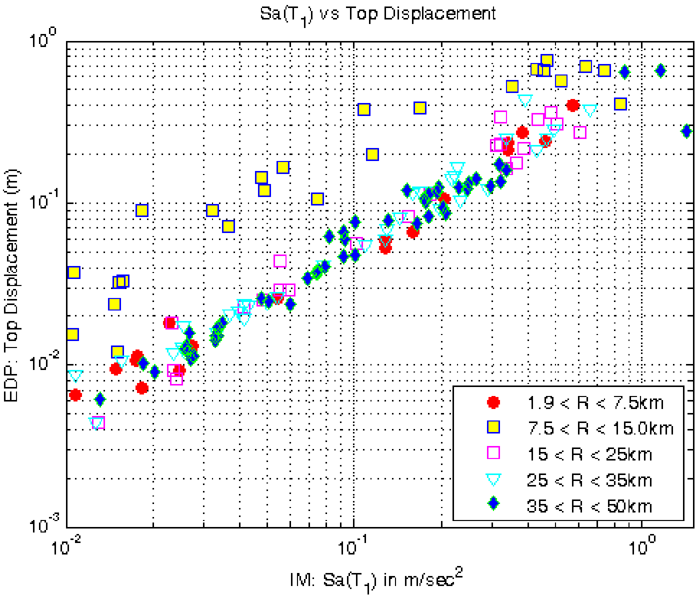

Figure 3. Top displacement vs spectral acceleration comparison for the 20-storey building

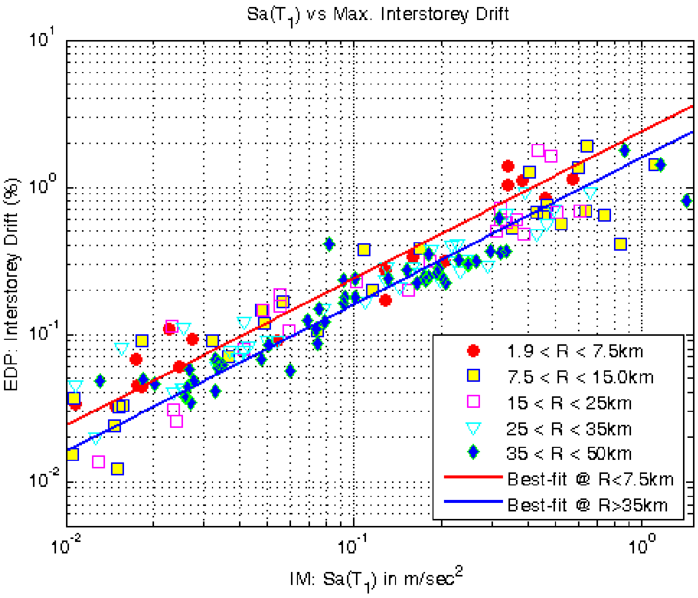

Figure 4. Max. inter-storey drift vs spectral acceleration comparison for the 20-storey building

The results shown in Figure 3 to Figure 6 readily highlight the difference in response for the case of R<7.5 km. The difference for the case of R being between 7.5 km and 15.0 km is not that clear however, suggesting that the critical region for the tall structures may be within the first 10 km. This conclusion needs to be verified also for other types of structures and different types of fault rupture mechanisms as well. A meaningfully different trend could not be obtained in this study for the case of 7.5 < R < 15.0 km.

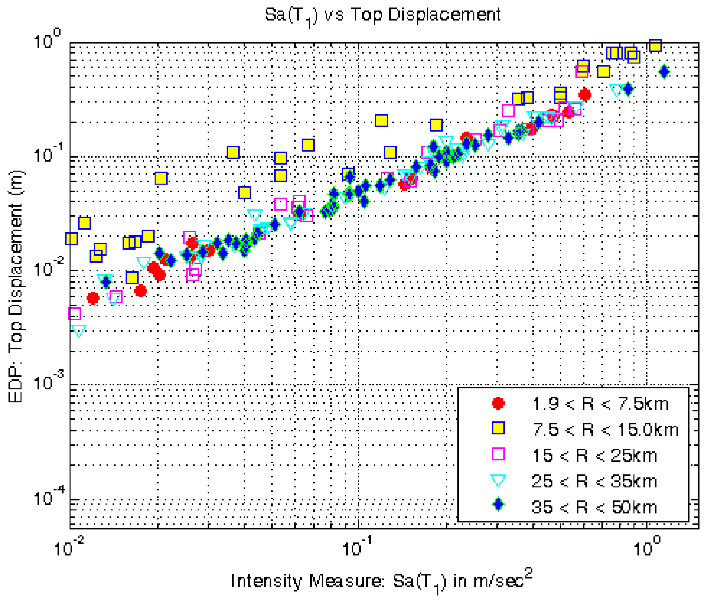

Figure 5. Top displacement vs spectral acceleration comparison for the 30-storey building

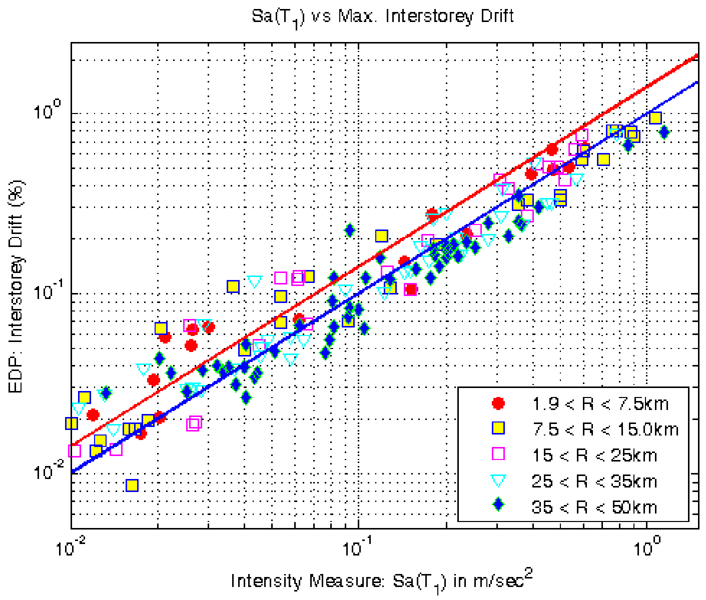

Figure 6. Max. inter-storey drift vs spectral acceleration comparison for the 30-storey building

An exercise on the trends obtained here can reveal the need for increasing the spectral demands in order to accurately represent and take into account the effects of near-field on the two tall structures studied here. The value of 3 % inter-storey drift could be attained, according to the trend values presented in Table 3, if 1.24 and 1.86 m/sec^2 spectral acceleration values were to be used for near-field and far-field record sets, respectively. In other words, the classic design procedure assumes that the 3 % inter-storey drift in the 20-storey structure would be achieved only if the spectral acceleration at the fundamental period reaches 1.86 m/sec^2. The analyses presented also show that 1.24 m/sec^2 spectral acceleration would be enough to push the structure to 3% inter-storey drift if the records used were from near field sources (i.e. R<7.5 km). This means that the design accelerations need to be multiplied with a correction coefficient, which would be 1.86/1.24=1.50 in the case of the 20-storey structure. The equivalent correction coefficient for the 30-storey structure is 1.35. This simple exercise concludes that the design accelerations need to be increased in the order of 35 to 50 % in case the tall structures designed are within a distance of 7.5 km from the possible epicentre.

A measure that can be taken in the design procedure against the near-field effects is artificially increasing the spectral demands, which can mitigate the lack of representing near-field effects and the augmented spectral values they entail. As mentioned, UBC (1997), for instance, provides a 50% increase, which is in agreement with the findings of this study as well. The displacement-based design, however, requires the change of the damped displacement spectrum achieved by changing the spectral reduction factor. Priestley et al. (2007) suggest the use of the formulae given in Equations (2) and (3). Equation (2) is intended for the case of far-field and Equation (3) is proposed for the case of near-field. The difference, as compared to other suggestions for spectral reduction factors, is given in Figure 7. For the case of the case study structures presented here, for instance, the equivalent effective damping is 8 and 9% for the 20- and 30-storey structures, respectively. This would require, according to Equations (2) and (3), and Figure 7, the demand to be increased approximately 25%, which is smaller than the ratios found in this study. The suggestion by Priestley et al. (2007) is expected to become closer to the expected values as the equivalent effective damping values increase.

$$\eta=[7/(\xi+5)]^{0.50} \tag{2}$$

$$\eta=[7/(\xi+5)]^{0.25} \tag{3}$$

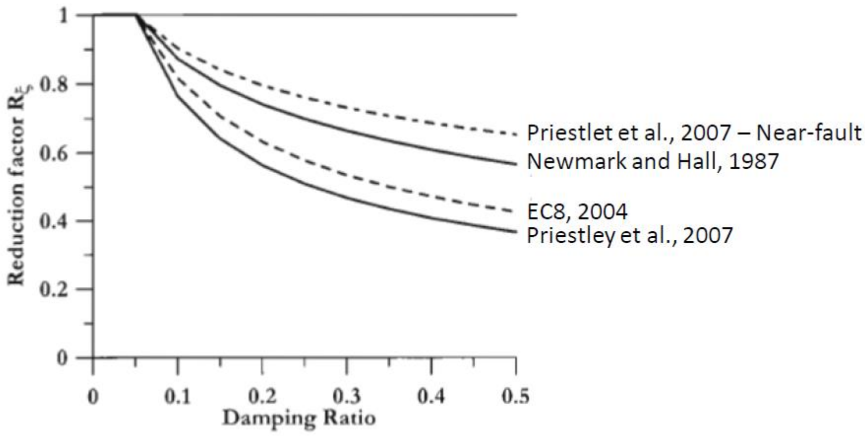

Figure 7. Comparison of the spectral reduction factor as function of the damping (Priestley et al., 2007)

CONCLUSIONS

Near-field records are rich in high frequencies and able to induce different seismic response on structures from the one designed for considering far-field conditions. Furthermore, the records with near-field nature are susceptible to create an unexpected response especially on long period structures dominated by higher modes.

The very objective of this study is to characterize the effects of the near-fault records on tall structures where the structural periods are long and the effects of the higher modes are prominent. In order to achieve this, two case-study structures, one 20-storey and another 30-storey, designed according to the Direct Displacement Based Design Procedure, have been analysed. Natural ground motion records were used for the analyses. The records have been grouped according to R, i.e. the epicentral distance, being varied among 0-7.5 km, 7.5-15 km, 15-25 km, 25-35 km and 35-50 km in 5 different bins. The analyses have been conducted in OpenSees (2013) where fibre-based distributed-plasticity elements were employed.

Though common, the use of top-displacement as an engineering indicator did not provide insight in the response differences between near-field and far-field records, as expected. The inter-storey drift ratios were employed as engineering demand parameter enabling the establishment of a relation between the findings and the design procedure.

The presented results show that the design accelerations need to be multiplied with a correction coefficient, which would be in the range of 1.5 in the case of 20-storey structure. Smilarly, the correction coefficient is 1.35 in the case of 30-storey structure. The simple procedure followed led to the conclusion that the design accelerations need to be increased in the order of 35 to 50 % in case the tall structures designed are in the range of 7.5 km or less from the possible epicentre.

The proposed increase in the design demand by UBC 1997 was found rather crude but safe for the two case studies examined even for an the epicentral distance less than 7.5 km. The suggestion reported in the direct displacement-based design for changing the spectra reduction factor (or in other words the damping modifier) underestimates the amount of increase required in the design demand for the examined structures, but is expected to be more accurate as the equivalent effective damping increases.

It is readily deduced that there is need for examining more complicated models, expand the number of case studies to other type of structures, include other fault rupture mechanisms in order to obtain a reliable quantification of the increase in demand expected on tall structures in the vicinity of the fault. Special focus should be place on tall structures that are constructed in a distance shorter that 10 km from the possible epicentre.

REFERENCES

Anderson JC and Bertero VV (1987) "Uncertainties in Establishing Design Earthquakes", *Journal of Structural Engineering*, 113(8).

Champion C and Liel A (2012) "The effect of near-fault directivity on building seismic collapse risk", *Earthquake Engineering and Structural* Dynamics, 41:1391–1409

Hall JF, Heaton TH, Halling MW, Wald DJ (1995) "Near-Source Ground Motion and its Effects on Flexible Buildings", *Earthquake Spectra*, 11(4):569–605.

Huang YN, Whittaker AS, Luco N (2008) "Maximum Spectral Demands in the Near-Fault Region", *Earthquake Spectra*, 24(1):319–341.

Iwan WD (1997) "Drift spectrum: Measure of demand for earthquake ground motions", *Journal of Structural Engineering*, 123(4).

Krawinkler H, Medina R, Alavi B (2003) "Seismic drift and ductility demands and their dependence on ground motions", *Engineering Structures*, 25:637–653.

Longjun X, Rodriguez-Marek A, Lili X (2006) "Design spectra including the effect of rupture directivity in the near-fault region", *Earthquake Engineering and Engineering Vibration*, 5(2):159–170.

MacRae GA, Morrow DV, Roeder CW (2001) "Near-Fault Ground Motion Effects on Simple Structures", *Journal of Structural* Engineering, 127(9):996–1004.

Malhotra PK (1999) "Response of buildings to near-field pulse-like ground motions", *Earthquake Engineering and Structural Dynamics*, 28:1309-1326.

Maniatakis CA and Spyrakos CC (2012) "A new methodology to determine elastic displacement spectra in the near-fault region", *Soil Dynamics and Earthquake Engineering*, 35:41-48.

Mander JB, Priestley MJN, Park R (1988) "Theoretical stress-strain model for confined concrete", *ASCE J Structural Engineering* 114(8):1804–1826

Menegotto M and Pinto PE (1973) "Method of Analysis for Cyclically Loaded R.C. Plane Frames Including Changes in Geometry and Non-elastic Behaviour of Elements under Combined Normal Force and Bending", *Symposium on the Resistance and Ultimate Deformability of Structures Acted on by Well Defined Repeated Loads*, Int. Association for Bridge and Structural Engineering, Switzerland, 15-22.

Newmark NM and Hall WJ (1982) "Earthquake Spectra and Design", EERI Monograph, Oakland, USA, 1982, 103pp.

OpenSees (2013) "Open System for Earthquake Engineering Simulation", *Pacific Earthquake Engineering Research Center, US* (opensees.berkeley.edu).

Pitarka A, Somerville P, Fukushima Y, Uetake T, Irikura K. (2000) "Simulation of near-fault strong-ground motion using Green's functions", Bulletin of the Seismological Society of America, 90(3):566-586.

Priestley MJN, Calvi GM and Kowalsky MJ (2007) "Displacement-based seismic design of structures", IUSS Press, Pavia, Italy.

Smyrou E, Priestley MJN, Carr A (2011) "Modelling of elastic damping in nonlinear time-history analyses of cantilever RC walls", *Bulletin of Earthquake Engineering*, 9:1559 -1578.

Somerville PG, Smith, NF, Abrahamson NA (1996) "Accounting for near-fault rupture directivity effects in the development of design ground motions", *Eleventh World Conference on Earthquake Engineering Proceedings*, Pergamon, Elsevier Science Ltd.

Somerville P (2002) "Characterizing near-fault ground motion for the design and evaluation of bridges", *Proceedings of the 3rd National Seismic Conference and Workshop on Bridges and Highways*, 28 April–1 May 2002, Portland, OR, pp. 137–148.

Tothong P, Cornell CA (2008) “Structural performance assessment under near-source pulse-like ground motions using advanced ground motion intensity measures”, Earthquake Engineering and Structural Dynamics 2008; 37:1013–1037.

UBC (1997) Uniform Building Code, International Conference of Building Officials, USA.