Journal of the Faculty of Environmental Science and Technology, Okayama University
Vol 5, No.1. pp. 113-119, February 2000

Ductility of RC Columns due to Strong Near Source Earthquakes

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(Received November 21 , 1999)

Near source earthquakes can produce strong vertical ground motions with large amplitude and high frequency content. In this paper the axial ductility behavior of RC columns due to near source earthquakes is investigated. The column is simplified to a SDOF system that only describes vertical vibrations of a structural column. The gravity load effect is represented by a pre-load. An elasto-plastic model accounting for different stiffness and strength in tension and compression is used in the analysis. The ductility demand as well as pseudo acceleration spectra are evaluated. The investigation shows that strong vertical ground motions should be considered in seismic design. From the results of this investigation suggestions for a seismic design in case of near source earthquakes can be derived.

Key words: *RC columns, ductility demand, near source earthquakes, strong vertical ground motions, pseudo acceleration spectra*

1 INTRODUCTION

In many of current seismic codes vertical earthquake load is neglected or treated just by scaling the amplitude of the horizontal load without a proper consideration of the frequency content. Records of recent earthquakes like Northridge (1994) and Kobe (1995) have indicated that peak vertical ground acceleration PVGA can be much larger than peak horizontal ground acceleration PHGA, especially near the source (Chouw, et al. 1999). During Kobe earthquake not only old but also new buildings suffered severe damages. Field investigations suggested that some of the damages due to recent earthquakes could be attributed to strong vertical ground excitations (Papazoglou, et al. 1996). Failure of many RC columns during the Kobe earthquake indicates that RC columns should have sufficient ductility to resist the strong vertical and horizontal ground motions. Up to now limited investigations on the nonlinear behavior of RC structures under strong vertical ground motions have been done. Elnashai, et al. (1996) studied the inelastic spectra for vertical vibration of RC columns where the ductility demand spectra for some near source earthquakes were considered. Christopoulos, et al. (1999) evaluated the effect of the near source vertical ground motions on the inelastic response of steel moment-resisting frames.

Bozorgnia, et al. (1996) studied the relationship between vertical and horizontal response spectra for the Northridge earthquake. Using records of recent strong earthquakes in US, Japan and Mexico Ohno, et al. (1996) evaluated the relation between vertical and horizontal components in terms of response spectra for seismic design. They applied some approximate methods to derive vertical acceleration response spectra from the spectra of horizontal ground motions rather than from records of vertical ground motions directly. A vertical earthquake load obtained by using this procedure does not reflect the natural fact of the ground motions, because near the source the difference between vertical and horizontal ground motions in frequency content is much more pronounced. Since the frequency content of a load defines which of the natural vibration modes of a structure will be excited by the ground motions, it therefore determines how strong a structure will suffer that earthquake. These studies show that it is important to define appropriate vertical and horizontal design spectra from recent near source earthquake records. Recent studies show that for certain constructions, like cantilever highway bridges, strong horizontal ground motions alone can produce large vertical inertia forces at the cantilever span (Liu, 1999). For this kind of constructions, strong vertical and horizontal ground motions surely should be taken into

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account in the design.

This study addresses the axial ductility behavior of RC columns during near source earthquakes and also investigates the vertical acceleration response spectra.

2 ANALYTICAL MODEL

The vertical vibration behavior of a column of RC buildings shown in Figure 1 is considered.

Vertical and horizontal ground motions in the near field can be very different in their amplitude and frequency content. Structures under vertical and horizontal ground excitations also behave differently, since in the vertical direction the structure is pre-loaded. The mass m of the SDOF system represents the total mass lumped at the upper end of the column. The pre-load accounts for the total dead and live load supported by this column. In order to investigate the effect of the pre-load a dimensionless axial force factor R_a, defined as the ratio of the pre-load to the product of the mass and the acceleration of gravity, is introduced. R_a may be less or larger than 1. For example, R_a of 0.5 might roughly represent an upper story column in a medium size building, while R_a of 1.5 represents a ground story column of the same building.

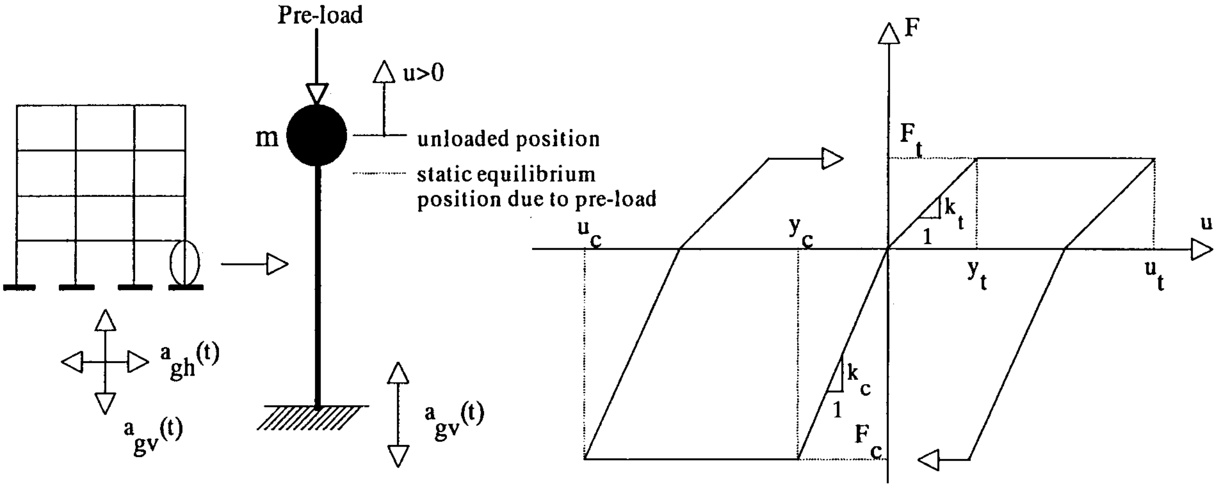


Fig. 1 Relationship between axial force and deformation of a RC column

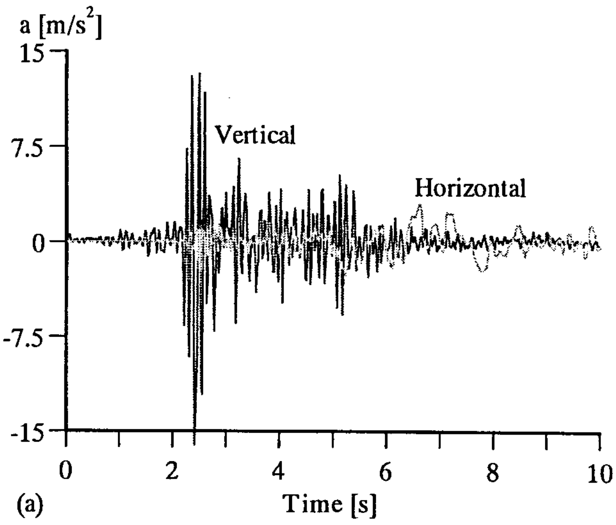
In order to describe the force-displacement relationship of the column a simple elasto-plastic model with different stiffness and strength in tension and compression is utilized. The stiffness ratio R_{sti} and the strength ratio R_{stre} are the ratio of compressive stiffness k_c to tensile stiffness k_t, and the ratio of compressive strength F_c to tensile strength F_t, respectively. These parameters depend only on the reinforcement ratio of the column, although k_c, k_t, F_c and F_t may be affected by many different factors as material properties and dimensions etc. The greater the reinforcement ratio is, the smaller R_{sti} and R_{stre} are.

Safety factor against static compressive failure R_{sf}, that is defined by the ratio of the design load to the actual load, is applied to the pre-load in order to estimate the compressive strength of the system. This safety factor is determined by the design code of the country considered. Each country may have different R_{sf} value.

Finally, in order to evaluate the column ductility we define axial compressive (tensile) ductility factor as the ratio of the maximum compressive (tensile) deformation $u_c(u_t)$ to the compressive (tensile) yield limit $y_c(y_t)$, respectively.

3 AXIAL DUCTILITY DEMAND AND PSEUDO ACCELERATION SPECTRA

In this study the column ductility for the case of Imperial Valley earthquake at 27.12 km, the Northridge earthquake at Arleta Fire Station and the Kobe earthquake at Kobe University is analyzed.



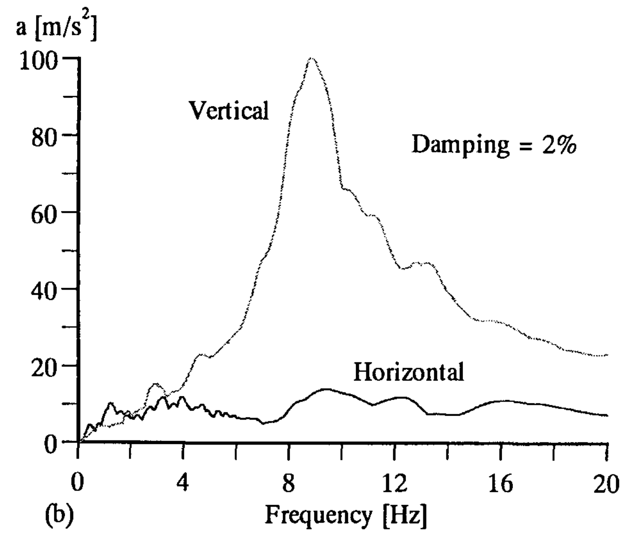


Fig. 2(a) and (b) Ground accelerations during Imperial Valley earthquake and their response spectra

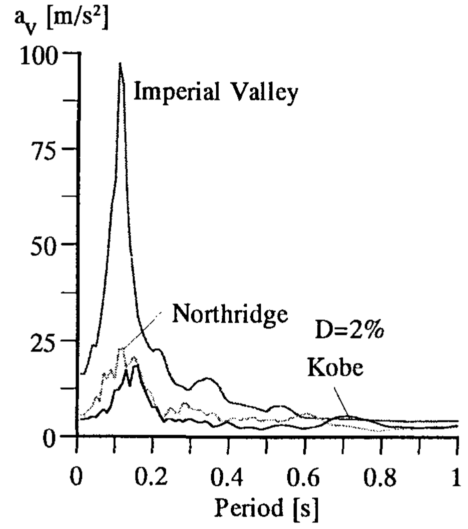
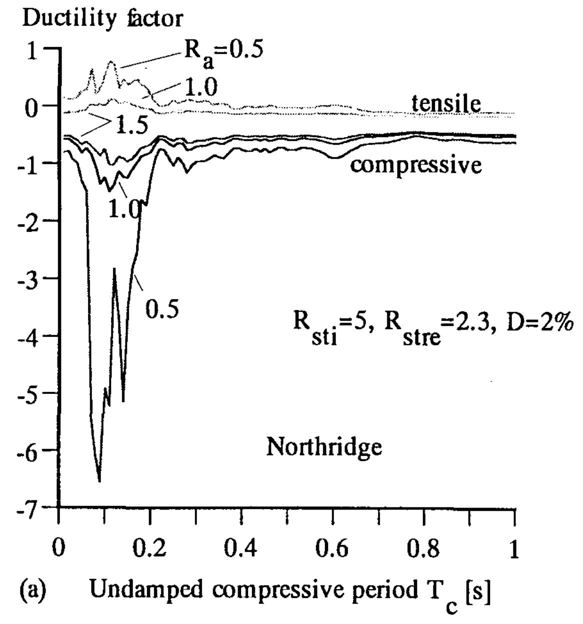


Fig. 3 Response spectra of vertical ground motions



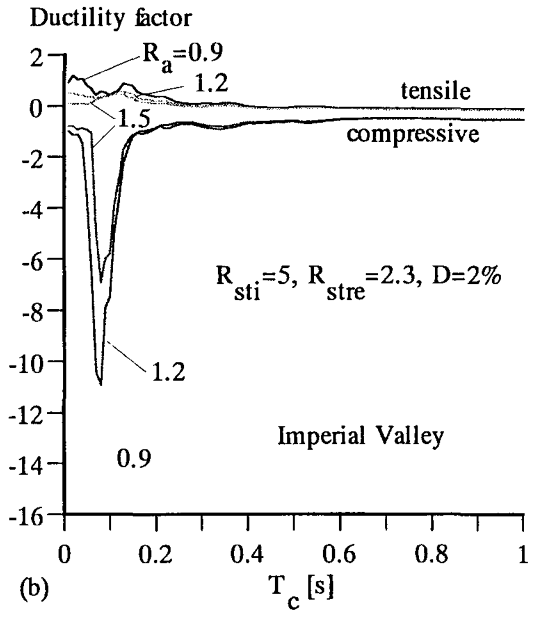


Fig. 4(a) and (b) Effect of pre-load on the axial ductility demand due to the Northridge and Imperial Valley earthquake, respectively

Fig. 2 shows the vertical and horizontal ground motions of the Imperial Valley earthquake and their response spectra. The PVGA is about 1.6g, the ratio of PVGA to PHGA is 4.8. The higher frequency content of the vertical ground motions can also be seen in Fig. 2(b). Fig. 3 gives the response spectra of the vertical components of these three considered earthquakes.

Fig. 4(a) and (b) show the influence of pre-load on the column ductility due to the Northridge and Imperial Valley earthquakes, respectively. A comparison of figure 3 and 4 shows the approximate correspondence between the ductility demand and the frequency content of the ground excitation. The ductility factor decreases with increasing pre-load. If the axial force factor or the pre-load increases, then the compressive yield limit becomes larger, because the compressive strength becomes stronger. Since the input energy remains the same, the ductility factor therefore decreases. Despite the safety factor of 2.5 the vertical ground excitation can cause column compression failure. For the case of Imperial Valley earthquake tensile yielding occurs for the axial force factor of 0.9. In this case the upper structure may uplift.

In Figure 5 due to different frequency content of the considered ground motions the highest ductility demands occur as expected at different predominant frequencies.

Figure 6 shows the effect of safety factor on the ductility demand of the column due to the Northridge earthquake. As expected the ductility demand decreases

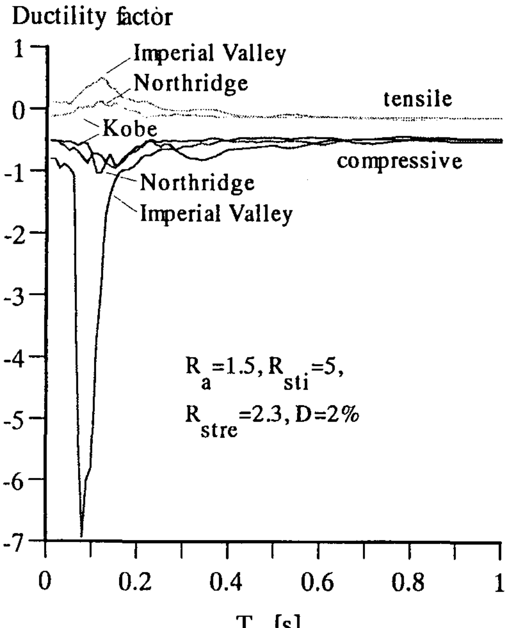


Fig. 5 Comparison of ductility demand

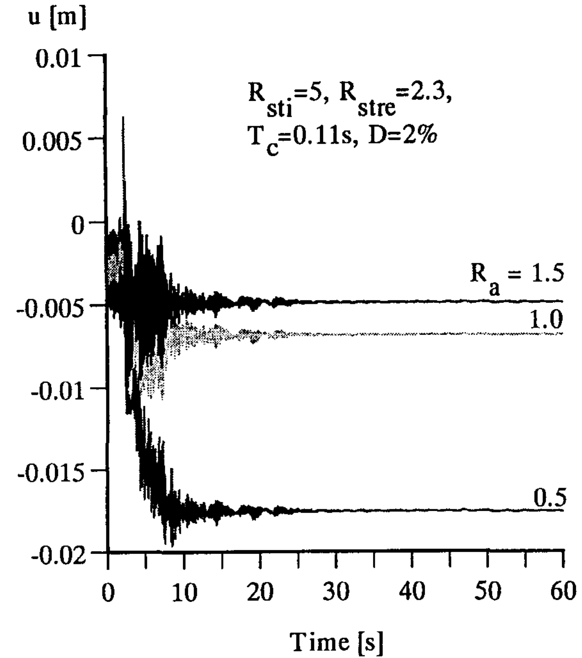


Fig. 7 Displacement time history of the column

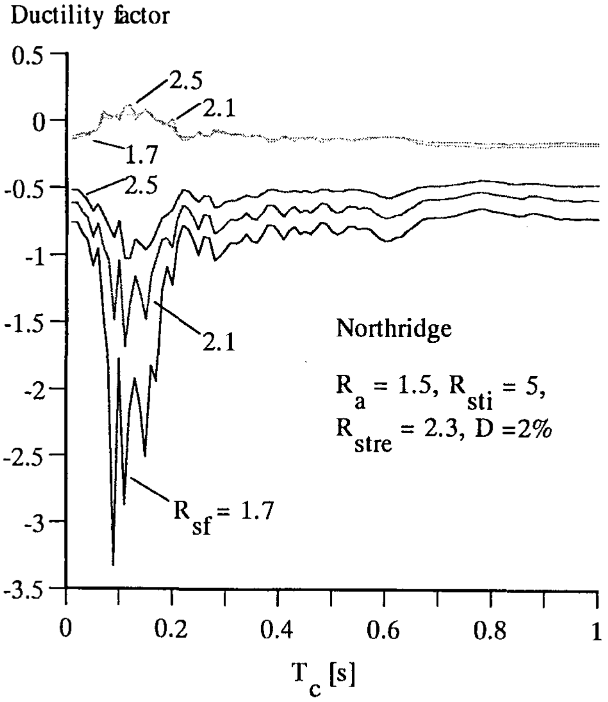


Fig. 6 Effect of the safety factor on column ductility

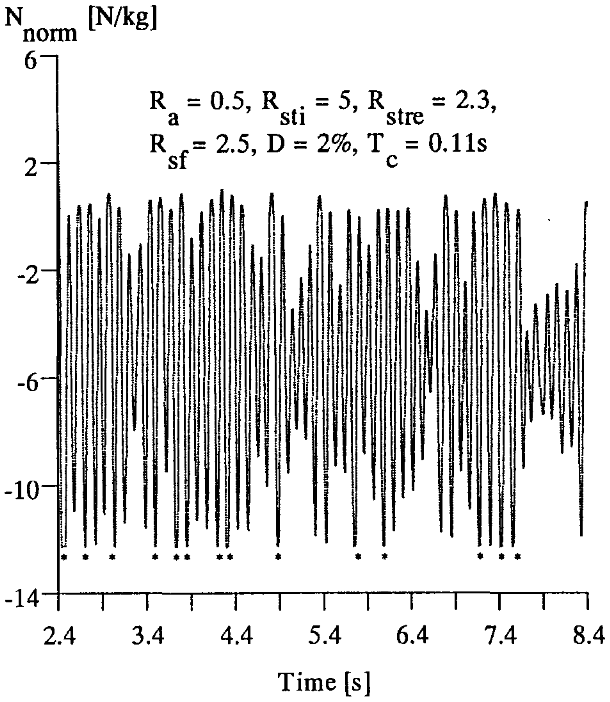


Fig. 8 Nonlinear normal force development for the case of Northridge earthquake

with increasing safety factor. For the safety factor of 1.7 - commonly used in many countries- the column ductility may not be sufficient, depending on design criteria.

Figure 7 shows the effect of pre-load on the development of the column displacement in the case of Northridge earthquake. Tension occurs in all considered levels of pre-load, even in the case of the axial force factor $R_a = 1.5$. At $R_a = 0.5$ the tensile displacement exceeds 6mm and the compressive one is nearly 2cm which displays the strong effects of the vertical ground motions. An increase of the axial force factor enlarges the compressive yield limit (see the explanation for figure 4). With a constant input energy the maximum and residual displacements therefore decrease.

The normal force in Figure 8 is for a system with 1kg mass. In case of a mass of 1000kg the normal force is 1000 times the normalized values. One can observe that reloading in tension occurs many times, and 14 reloading cycles accompanied by compressive plastic flow,

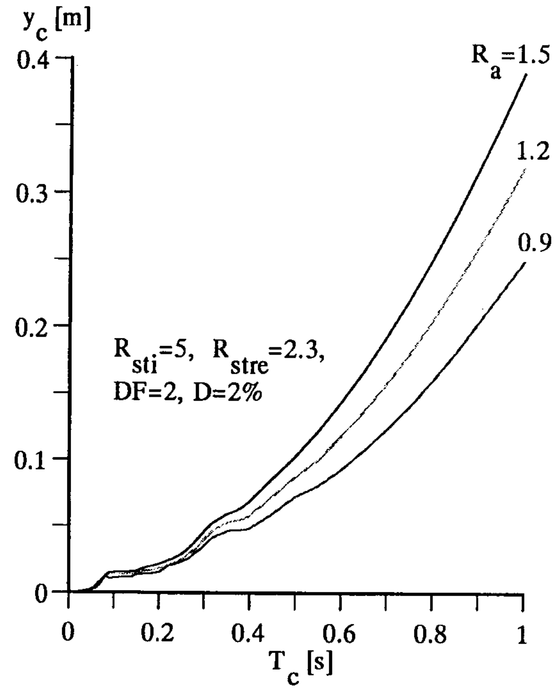


Fig. 9 Compressive yield limit of the column

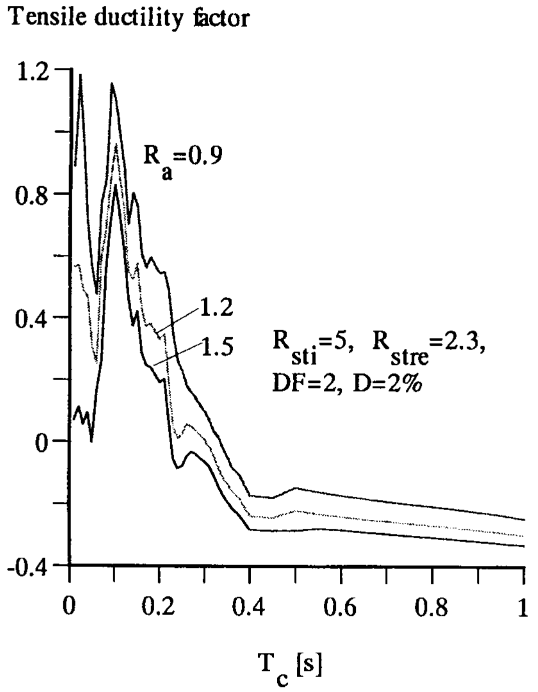


Fig. 10 Tensile ductility factor of the column

indicated by the symbol * , occur in the first 9 seconds. This implies the possibility of fatigue of the RC columns.

Figure 9 shows the influence of pre-load on compressive yield limit for a prescribed ductility factor of 2.0 due to the Imperial Valley earthquake. Figure 10 shows the tensile ductility factor for the same condition.

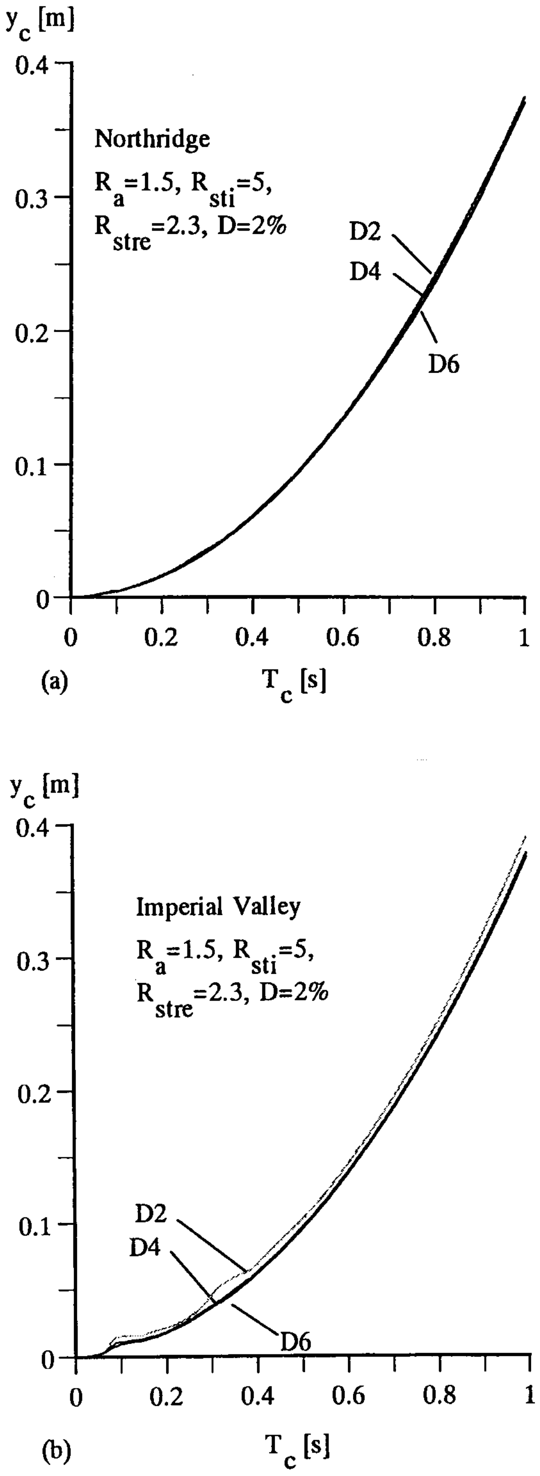


Fig. 11(a) and (b) Compressive yield limit of the column due to Northridge and Imperial Valley earthquake, respectively

At high frequency range the structure is very stiff, the pre-load therefore has only small effect on the static deformation, the compressive yield limit changes slightly with different levels of R_a. But at low frequency range the effect of the pre-load can not be neglected. From Figure 10 it can be seen that the tensile ductility factor decreases if the pre-load increases. Since the input energy does not change, the energy consumed in compression rises. The compressive yield limit is larger at higher level of pre-load, provided the same compressive ductility factor of 2.0 is obtained.

Figure 11(a) and (b) show the compressive yield limit at different levels of ductility factor equal 2, 4, and 6 (indicated by D2, D4 and D6) due to the Northridge earthquake and the Imperial Valley earthquake, respectively.

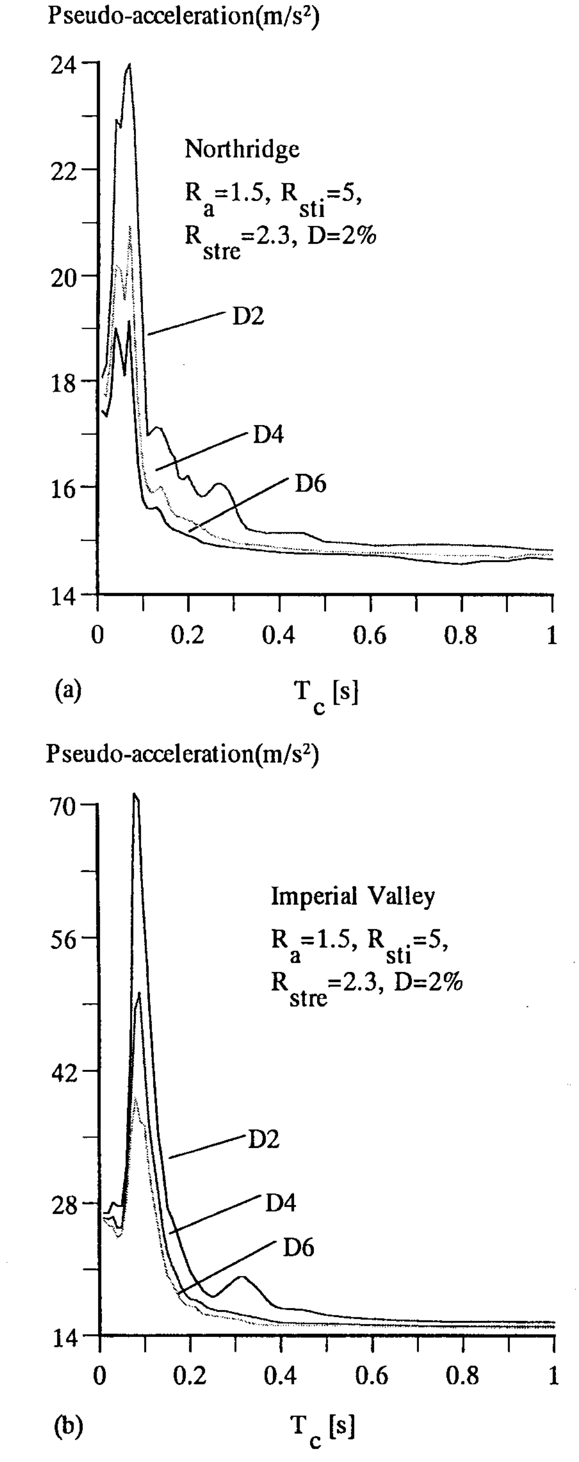


Fig. 12(a) and (b) Compressive pseudo acceleration of the column due to Northridge and Imperial Valley earthquake, respectively

Since the input energy is same, in order to obtain larger ductility factor the compressive yield limit must be smaller. The compressive yield limit increases if the system period becomes larger, since the column becomes more deformable in the axial direction. Since PVGA of the Imperial Valley earthquake is much larger than that of the Northridge earthquake, the difference of the compressive yield limit between different levels of ductility factor in Figure 11(b) is greater than its counterpart in Figure 11(a).

Figure 12 (a) and (b) give the compressive pseudo acceleration at different levels of ductility factor due to the Northridge and Imperial Valley earthquake, respectively. Since the compressive pseudo acceleration is the product of the compressive yield limit and the square of circular system frequency, the compressive pseudo acceleration therefore decreases if the ductility factor rises. We can also observe the approximate correspondence between the pseudo acceleration response, which is the compressive force per unit mass and corresponding to the vertical design load, and the frequency content of the ground excitation. This figure is useful to gain suitable vertical design spectra of near source earthquakes, because it is calculated from the vertical ground motions directly rather than from the horizontal ground motions.

4 CONCLUSIONS

The frequency content and magnitude of the vertical ground motions have significant effects on the column ductility demand and pseudo acceleration response. If the pre-load increases, the axial ductility and residual displacement of RC columns decreases, while the compressive yield limit of the column for a prescribed ductility factor becomes larger. Even for the large safety factor of 2.5 the axial column ductility can be insufficient to prevent compression failure. The study confirms that strong vertical ground excitations should be considered in seismic design. The compressive yield limit and pseudo response acceleration falls with increasing ductility factor. The compressive pseudo acceleration, calculated from the vertical ground motions, can be used to extract proper vertical acceleration design spectra.

ACKNOWLEDGEMENTS: The first author strongly acknowledges the support from The Japanese Ministry of Education, Science, Sports and Culture for his research stay.

REFERENCES

Bozorgnia, Y., Niazi, M. and Campbell, K. W. (1996): Relationship between vertical and horizontal response spectra for the Northridge earthquake, *Proc. of 8th World Conference on Earthquake Engineering*, Paper No. 893.

Chouw, N. and Hirose, S. (1999): Behaviour of a frame structure during near-source earthquakes, *Proc. of 4th EURODYN, Prague, Balkema*, pp. 1191-1196.

Christopoulos, C., Filiatrault, A. and Leger, P. (1999): Effects of near-fault vertical seismic accelerations on the response of steel moment-resisting frames, *Proc. of 8th Canadian Conf. on Earthquake Engineering, Vancouver*, pp. 293-298.

Elnashai, A. S. and Papazoglou, A. J. (1997): Procedure and spectra for analysis of RC structures subjected to strong vertical earthquake loads, *Journal of Earthquake Engineering*, 1-1, pp. 121-155.

Liu, Q. Y. (1999): Inelastic seismic design verification of thin-walled steel bridge piers, *Doctor Thesis, Nagoya University*, 99pp.

Ohno, S., Kohno, T., Abe, K., Masao, T., Iizuka, S. and Uebayashi, H. (1996): Method of evaluating horizontal and vertical earthquake ground motions for aseismic design, *Proc. of 8th World Conf. on Earthquake Eng.*, Paper No. 1791.

Papazoglou, A. J. and Elnashai, A. S. (1996): Analytical and field evidence of the damaging effect of vertical earthquake ground motion, *Earthquake Engineering and Structural Dynamics*, Vol. 25, pp. 1109-1137.