SEISMIC BEHAVIOR OF A REINFORCED CONCRETE BUILDING DUE TO LARGE VERTICAL GROUND MOTIONS IN NEAR-SOURCE REGIONS

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SUMMARY

For investigating the influence of strong vertical motions in the near-source regions on building structures, we conducted an extensive series of seismic response analyses of a reinforced concrete building. The input motions used in the analyses were the accelerations recorded at the El Centro Array No. 6 during the 1979 Imperial Valley, California, earthquake and at the JMA Kobe during the 1995 Hyogo-Ken-Nanbu, Japan, earthquake. The building was designed based on the current Japanese seismic building code. It was modeled as a two-dimensional planar frame using non-linear elements to account for the bending moment-axial force interaction of the columns. The soil and structure interaction was also taken into account. The dynamic response analyses were performed for three cases of the input motions: the vertical motion only, the horizontal motion only, and both the vertical and horizontal motions. PGA of the vertical motion at El Centro Array No. 6 was 1490 Gal. The response of the model to the vertical motion was so large, but the model did not yield. The bottoms of the columns of the model yielded only by the horizontal motion of PGA of 424 Gal. The damage caused by the horizontal motion only was similar to that caused by the vertical and horizontal motions because of the time lag between the large response to the vertical motion and that to the horizontal motion. For JMA Kobe motion, severe damage was caused by the horizontal motion only because of the large horizontal acceleration of PGA of 818 Gal. The amplification factor to the vertical motion of PGA of 330 Gal was not so large as to affect the inelastic behavior of the model. The influence of the vertical motion was relatively small. Our study concluded that the strong vertical motions in the near-source regions had little influence on the damage to the building structure.

INTRODUCTION

The 1995 Hyogo-Ken-Nanbu, Japan, earthquake (M 7.2) occurred very close to the big city of Kobe, and large peak accelerations were recorded at the JMA (Japan Meteological Agency) Kobe. Large accelerations had also been recorded during the 1993 Kushiro-Oki, the 1993 Hokkaido-Nansei-Oki, and the 1994 Sanriku-Far-Off earthquakes since the 1968 Tokachi-Oki earthquake. However, the damage in these earthquakes was much less than that in the Hyogo-Ken-Nanbu earthquake. This is because the Hyogo-Ken-Nanbu earthquake was caused by the active faults in the land, very close to the big city, while the others occurred under the sea.

In these four years, detailed studies have been conducted to estimate the input earthquake motions in the zone of the seismic intensity of VII on the JMA scale and to investigate their effect on the damage to the structures. One of the aspects of the ground motions recorded in near-source regions is that vertical ground motions are much larger than those in far-source regions. Several researchers (Architectural Institute of Japan, 1997) suggested the

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influence of the vertical ground motions was significant for the substantial damage to the piers of the reinforce-concrete bridges. On the other hand, the current Japanese seismic building code does not regulate the force created by the vertical ground motions. The vertical ground motions have been of low interest for the seismic design of buildings.

According to the above discussion, the influence of strong vertical ground motions in the near-source regions on building structures was studied in this paper. A typical moment-resisting frame structure of reinforced concrete was chosen for the study. This structure was designed based on the current Japanese seismic design code. The earthquake motions used here were the records at the JMA Kobe during the 1995 Hyogo-Ken-Nanbu, Japan, earthquake and those at the El Centro Array No. 6 during the 1979 Imperial Valley, California, earthquake. The non-linear dynamic response analyses were performed for three cases of the input motions: the vertical ground motion only, the horizontal motion only, and both the vertical and horizontal motions combined.

THE EARTHQUAKE RECORDS USED IN THE STUDY

Prior to the dynamic response analyses, we reviewed the feature of the following two earthquake records obtained in the near-source regions:

(a) El Centro Array Nos.1-7 and Nos.10-13, the 1979 Imperial Valley earthquake (M6.9, focal depth 10 km)

(b) JMA Kobe, the 1995 Hyogo-Ken-Nanbu earthquake (M7.2, focal depth 14 km)

Figure 1 shows the relation between peak ground accelerations and fault distances. A series of El Centro Array is useful to understand the feature of the ground motions in near-source regions (Porcella *et al*., 1982). PGA of the vertical motions of El Centro Array increases significantly in accordance with approaching the fault. PGA of 818 Gal of the horizontal motion recorded at JMA Kobe was largest in these records. However, PGA of 1490 Gal of the vertical motion recorded at El Centro Array No. 6 was tremendously large. The ratio of PGA of the vertical motion to that of the horizontal motion was about 3.5, although the ratios at most of other sites were less than 1.0. In this study, we used the records at El Centro Array No.6 as well as the records at JMA Kobe for the dynamic response analyses.

Figure 2 shows the acceleration time histories, and Figure 3 shows the response spectrum of these ground motions. It is clear from these figures that the very large vertical PGA at El Centro Array No. 6 appreared in the primary waves but not in the secondary waves and that the vertical motions have a very large power at the period of about 0.1 s. Mueller *et al*. (1982) explained that this peak had been caused by the site amplification of the surface soil including ground water.

ANALYTICAL MODEL OF THE BUILDING

Figure 4 shows the analytical model of the building used in the study. The building was five-story, three-span, reinforced-concrete, moment-resisting frame. We designed it based on the current Japanese seismic building code and strengthened some elements to provide it with the lateral capacity of the base shear coefficient of 0.3.

The building was modeled as an assembly of non-linear frame elements, including vertical, horizontal, rotational springs to account for the effect of the soil-structure interaction. Frequency dependent complex stiffness of these springs were calculated (Kawase *et al*., 1982) at each site where the input ground motions were recorded, and a representative complex stiffness was fixed at the fist-mode frequency of the soil-structure interaction system.

The beams were modeled by the two-component model (Giberson, 1969) which consisted of an elastic beam in the middle and non-linear rotational springs at both ends. Takeda model (Takeda *et al*., 1970) was used for the rotational springs. Each beam was divided into four sub-beams to account for the vertical vibration. The columns were modeled by the multi-spring model (MS model, Lai *et al*., 1994) to account for the bending moment-axial force interaction. Figure 5 shows the outline of the MS model. This model consisted of an elastic beam in the middle and independent non-linear axial springs at both ends. Various types of the configurations of non-linear axial springs have been proposed for the MS model. In this study, we used a configuration of nine non-linear springs (five for concrete and four for reinforcement). Figure 6 shows the hysteresis model for each material. Moreover, an additional lateral force generated by P-Δ effect was taken in account. A damping ratio of two percent to critical was adopted at the fundamental period of 2.0 Hz of the fixed-base structure. The mass was concentrated at each node of the beam-column joint and at the three joints connecting the four sub-beams. Table 1 summarizes the result of mode analyses.

The response analyses were conducted in two steps. In the first step, a constant vertical acceleration of 980 Gal (gravity) was introduced to generate the long-term stress in the members. Next, dynamic response analyses were performed for three cases of input motions: vertical ground motion only, horizontal motion only, and both the vertical and horizontal motions combined. The time increment of the motinos was 0.01 s for El Centro Array No. 6 and 0.02 s for JMA Kobe. Step-by-step direct time integration was used assuming constant average acceleration and a time increment of 0.0005 s. Duration of dynamic response analyses was 20.0 s.

RESULTS OF THE DYNAMIC RESPONSE ANALYSES

El Centro Array No.6

Figure 7 shows the orbits of the bending moment and the axial force obtained at the bottom of the exterior column at the first story for the El Centro Array No.6 motions. Tension force was generated in the column for the vertical motion only because of the tremendously large vertical acceleration of PGA of 1490 Gal. However, the column did not yield by the vertical motion only. It yielded only by the horizontal motion of PGA of 424 Gal. The influence of the vertical motion was seen clearly at the orbit for both the horizontal and the vertical motions. The orbit consists of two parts: the one is dominated by the vertical motion and the other is dominated by the horizontal motion. This fact shows that the time lag exists between the large response to the vertical motion and that to the horizontal motion.

Figure 8 compares the variation range of the axial force in the exterior columns with that in the interior columns. The vertical motion strongly affected to both of the interior and exterior columns at every story. Tension force was generated in all of the columns by the vertical motion only. The range of the axial force variation for the vertical motion was almost same as that for both the vertical and horizontal motions. This feature was seen in both of the interior and exterior columns.

Figure 9 shows the peak ductility ratios obtained by the analyses for the horizontal motion only and both the horizontal and vertical motions, indicating the influence of the vertical ground motion to the inelastic behavior of the building structure. In spite of the significant influence of the vertical motion on the column axial force variation, these two figures are similar because of the time lag between the large response to the vertical motion and that to the horizontal motion. If no time lag, the vertical motion might be expected to cause the significant effect to the interaction of bending moment-axial force of the column. The damage was mainly caused by the horizontal motion only.

JMA Kobe

Figure 10 shows the orbits of the bending moment and the axial force obtained at the bottom of the exterior column at the first story for the JMA Kobe motions. The axial force remains within the compression region for the vertical motion only. The orbit for the horizontal motion only reached at the both side of yield surface. The columns yielded by the horizontal motion only because of the large horizontal acceleration of PGA of 818 Gal. The shape of orbit for the horizontal motion is quite similar to that for both the horizontal and vertical motions.

Figure 11 shows the variation range of the column axial force. The vertical motion strongly affected on the interior column axial force variation. This is because the vertical load supported by the interior columns is larger than that by the exterior columns. On the other hand, the horizontal motion induced the overturning moment to the structure and strongly affected on the axial force of the exterior columns. This feature was not seen for El Centro Array No.6. The effect of the vertical motion is much less than that of the horizontal motion for the exterior columns. Tension force was generated in the exterior columns located at the lower stories for the horizontal motion only. The variation range at each story for the horizontal motion only is almost the same as that for both the vertical and horizontal motions.

Figure 12 shows the peak ductility ratios. The ductility ratios for both the vertical and horizontal motions are somewhat larger than those for the horizontal motion only. No strong effect on the damage by the vertical motion can be seen at Figure 12. This is because the response by the vertical motion is so small that its effect is hidden by the effect of the large horizontal ground motion of 818 Gal. Finally, the vertical motion of the JMA Kobe records has no strong effect on the inelastic behavior of the model as well as El Centro Array No.6 records.

CONCLUSIONS

The influence of strong ground motions in the near-source regions on structures was studied. We conducted an extensive series of non-linear dynamic response analyses of a reinforced concrete building, using two of typical strong ground motions in the near-source regions: JMA Kobe and El Centro Array No.6. Different aspect of those vertical motions was seen at the analytical results. For El Centro Array No.6 records, the time lag existed between the peak response of the vertical and that of horizontal motions. For JMA Kobe records, the response of the vertical motion was much lower than that of the horizontal motion. For both records, the horizontal ground motion only caused significant damage to the building. The building was not damaged by the vertical ground motion only, even by the large acceleration of PGA of 1490 Gal. It was concluded that the vertical ground motion had little influence on the damage to the building.

The conclusion of this study was derived from the limited configuration of one type of buildings and two types of strong ground motions in the near-source regions. Future study for various types of building structures and ground motions is required to get a more general aspect of the influence of the ground motions in the near-source regions.

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Table 1: Result of mode analyses of the building model used in the study

(Hz)

site	mode		
	1st	2nd	3rd
El Centro Array No. 6	1.96 (1.31,0.00)	5.96 (0.48,0.00)	8.33 (0.00,1.31)
JMA Kobe	2.00 (1.30,0.00)	6.01 (0.47,0.00)	9.70 (0.00,1.43)

(x, z): participation factor

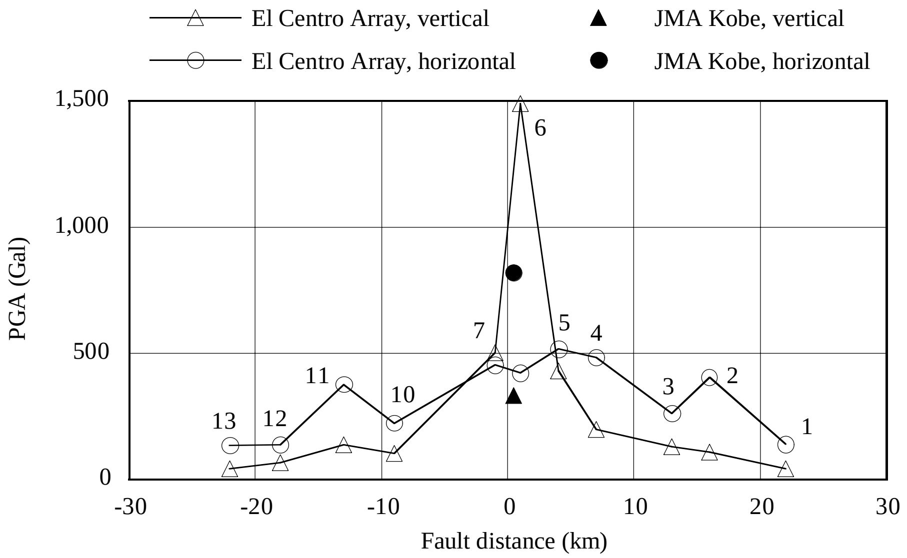


Figure 1: Distribution of peak ground accelerations

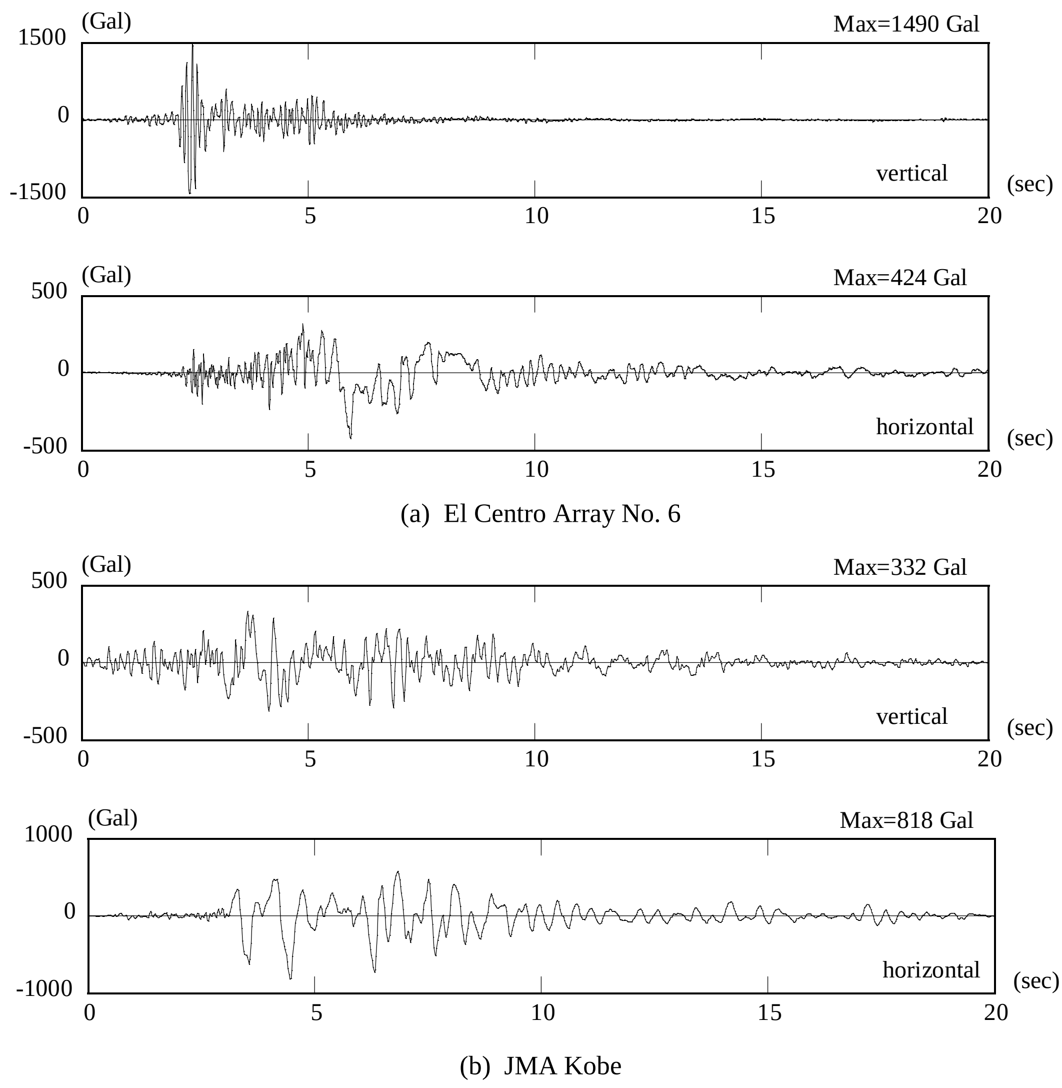


Figure 2: The ground acceleration time histories used for the dynamic response analyses

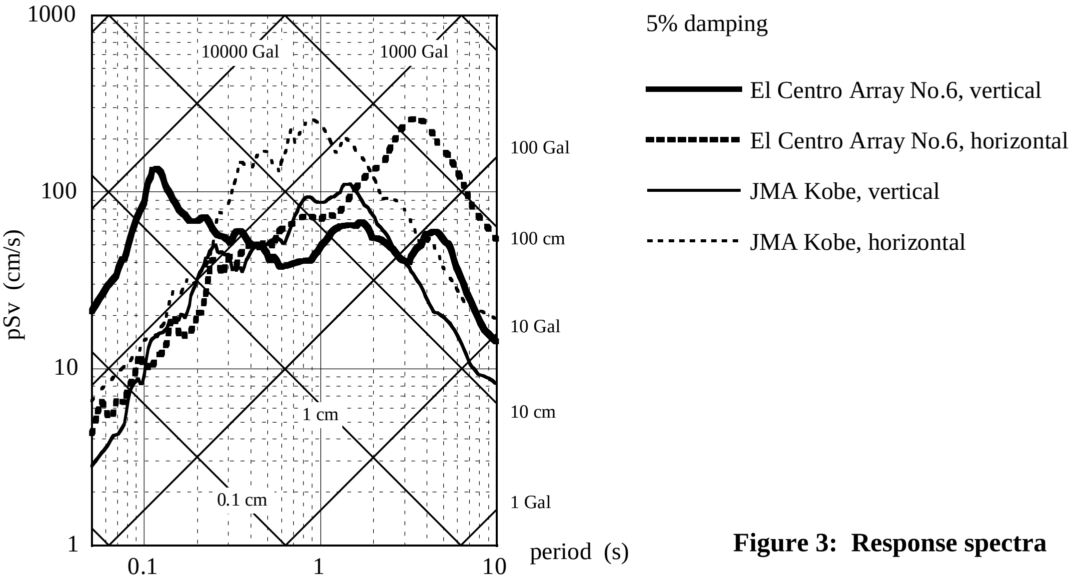


Figure 3: Response spectra

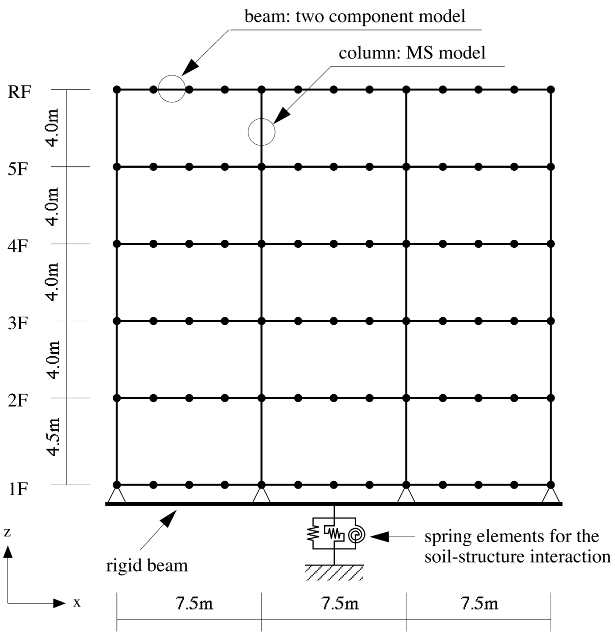


Figure 4: Two dimensional planar frame model

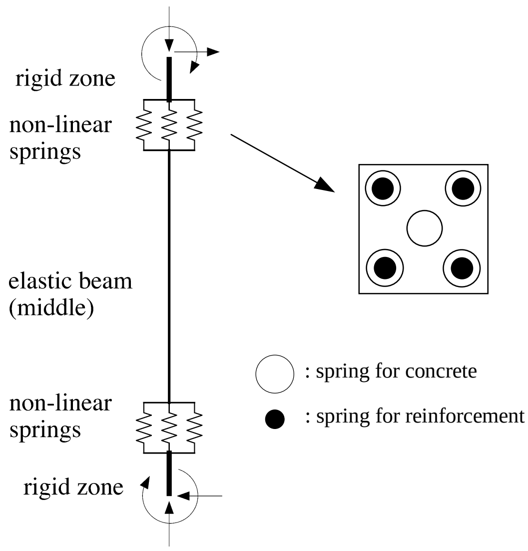


Figure 5: MS model for columns

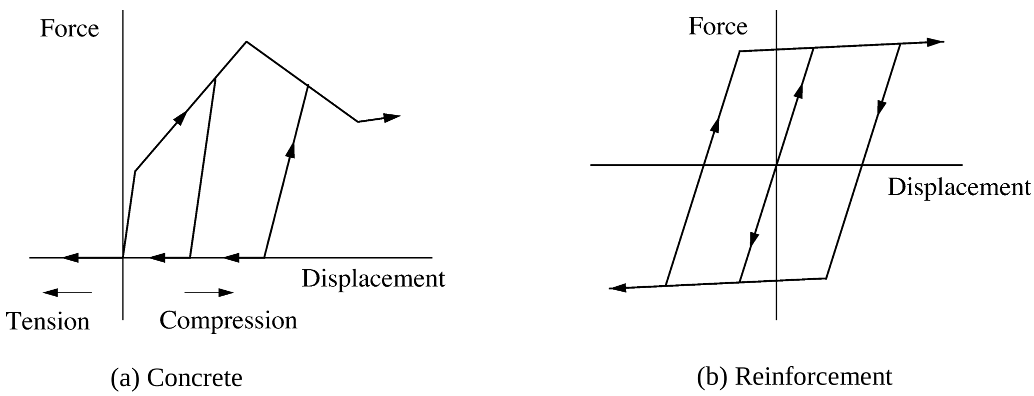
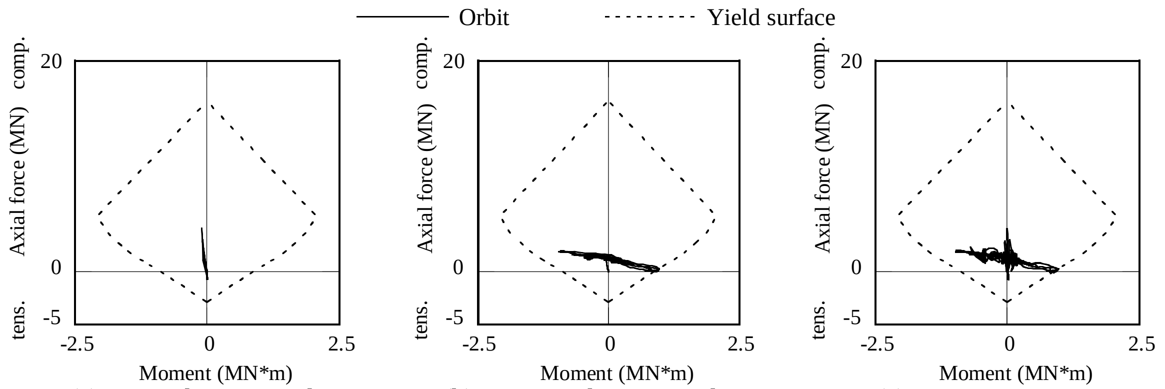


Figure 6: Hysteresis for MS model



(a) Vertical motion only (b) Horizontal motion only (c) Hor.+Ver. motion

Figure 7: Moment-axial force orbits of the exterior column for the El Centro Array No.6 motions

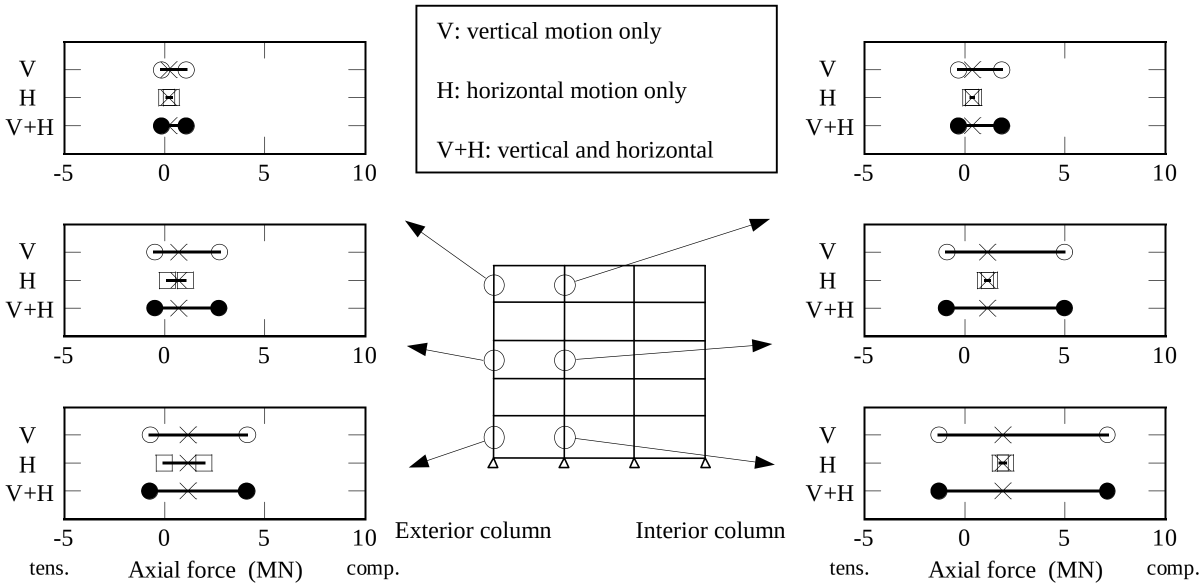
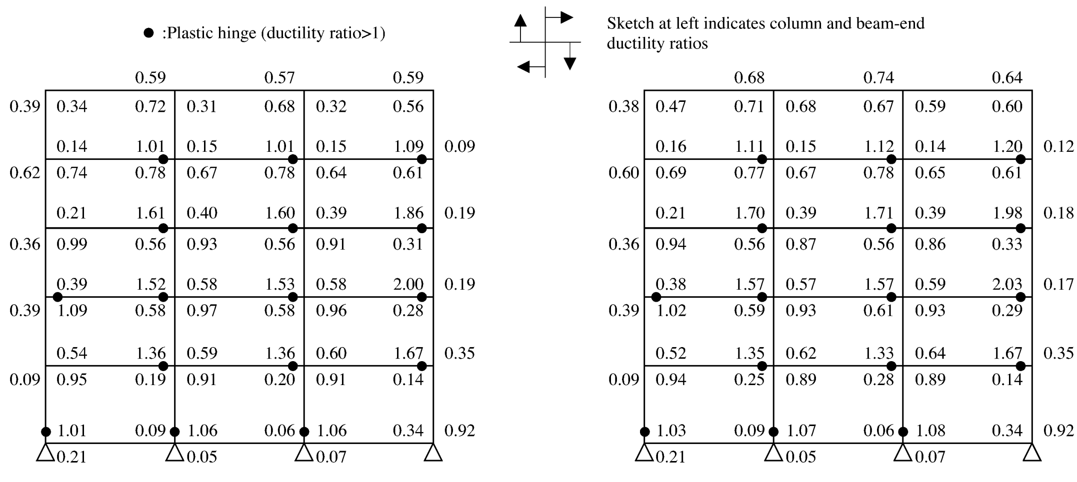
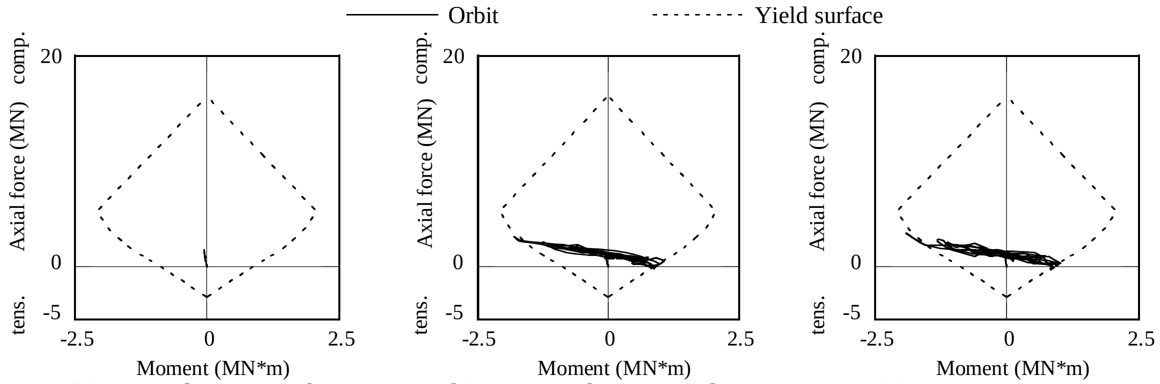


Figure 8: Axial force variation range of the columns for the El Centro Array No.6 motions



(a) Horizontal motion only (b) Hor.+Ver. motion

Figure 9: Peak ductility ratios in the model for the El Centro Array No.6 motions



(a) Vertical motion only (b) Horizontal motion only (c) Hor.+Ver. motion

Figure 10: Moment-axial force orbits of the exterior column for the JMA Kobe motions

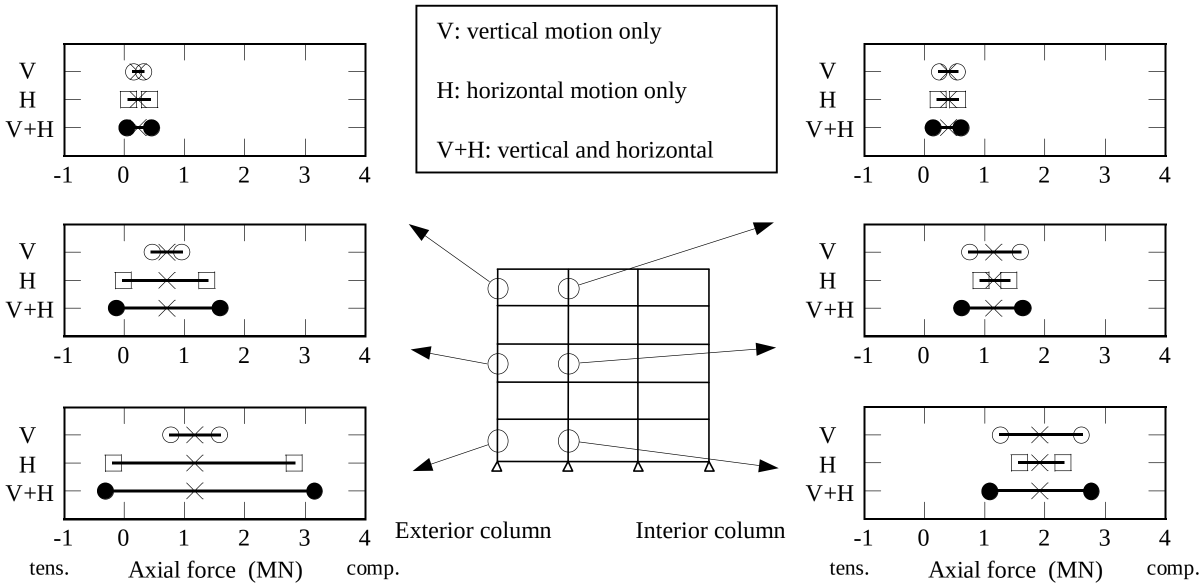
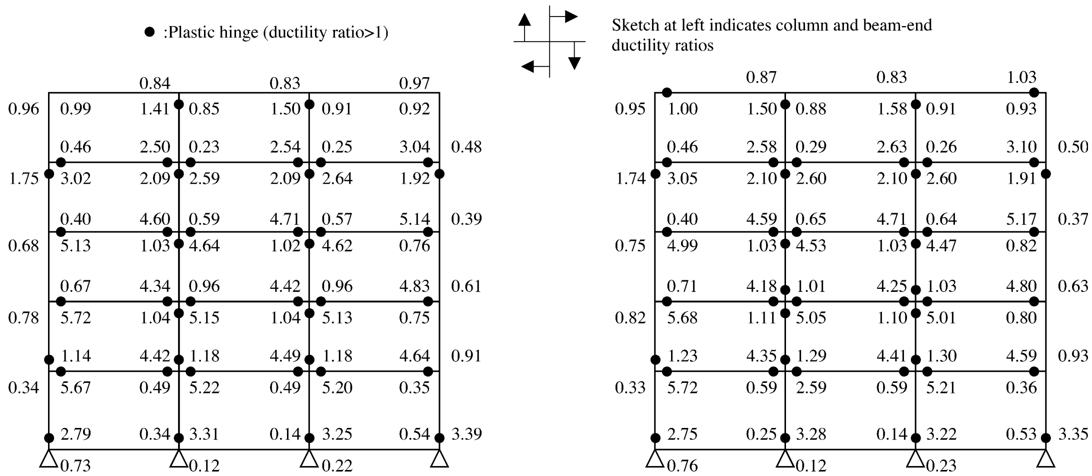


Figure 11: Axial force variation range of the columns for the JMA Kobe motions



(a) Horizontal motion only (b) Hor.+Ver. motion

Figure 12: Peak ductility ratios in the model for the JMA Kobe motions