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SEISMIC PERFORMANCE OF HIGH-RISE R/C STRUCTURES SUBJECTED TO VERTICAL EARTHQUAKE MOTION

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Abstract

This study is aimed at determining earthquake performance of RC structures under the vertical ground motion. The time-history analysis of a high-rise R/C structure designed in compliance with the Turkish Seismic Code requirements was conducted including and excluding the vertical earthquake motion. The earthquake records were selected according to the ratio of the vertical peak acceleration to the horizontal peak acceleration (V/H). Frequency content of the ground motions were also identified to investigate their influence on seismic performance of the structure. Based on the results of previous linear time-history analyses, the earthquake performance of the structure was estimated to change with varying the V/H ratio and earthquake duration since higher vertical accelerations were found to induce higher overturning moments at the base of the structure. Considering this conclusion, failure investigation was conducted to evaluate the earthquake performance of the high-rise R/C structure. In order to determine the effect of vertical seismic action on earthquake performance, earthquake loading conditions including the horizontal (H) and the vertical (V) earthquake motion were also taken into account. The earthquake performances of the structure under both of (H) and (H+V) loading conditions were examined and the results were compared. These comparative results indicated that the desired earthquake performance level of the structure could not be provided under (H+V) loading condition, and that damage level of the structures subjected to (H+V) loading was more severe than that of (H) loading. The current study indicated that the earthquake resistant design philosophy and the corresponding retrofitting approach should be specified by also taking the vertical earthquake motion into consideration.

Keywords: vertical earthquake motion; earthquake performance; high-rise R/C structures

1. Introduction

Severe past earthquakes, such as Loma Prieta 1989, Northridge 1994 and Kobe 1985, were observed to cause brittle failure of the load-bearing members (tension, compression and shear failures) of structures. Earthquakes not only induce horizontal ground motion in two orthogonal directions, but also vertical ground motion. The vertical ground motion is also responsible for the brittle failure of the members of a structural system, particularly when the variation of this component in time is more dominant than the variations of the horizontal ground motion components. Nonetheless, the vertical ground motion is generally disregarded in the earthquake-resistant design of structural systems for two main reasons. First, the energy induced by the vertical component of the ground motion to a structure is considered to be negligible when compared to the energy contents of the horizontal ground motion components. Second, the structural systems, originally designed to resist vertical forces, are assumed to resist the additional vertical forces induced by the vertical component of a ground motion.

Previous researchers directed their attention to the question of whether the vertical ground motion can be ignored in structural analyses or not. The analytical and observational findings of Papazoglou ve Elnashai [1] indicated that the vertical ground motions caused significant damage in earthquake-resistant structures and the periods of a structure and a ground motion were more influential than the energy content of the earthquake on the earthquake performance of the structure. Ambraseys and Simpson [2] developed equations for vertical acceleration spectra based on the magnitude, distance to source and site geology of an earthquake. Elnashai and Papazoglou [3] developed bilinear inelastic acceleration spectra to be used in modal analyses of structures subjected to vertical ground motions. Bozorgnia et al. [4] found out that the vertical dynamic characteristics of structures played an important role in the magnitudes of their vertical spectral accelerations, based on an investigation on twelve instrumented structures subjected to the Northridge ground motion. The study of Ambraseys and Douglas [5] on single-degree-of-freedom systems subjected to 186 different near-field earthquake records yielded to the conclusion that the vertical seismic action was negligible compared to horizontal seismic action. Elgamal and He [6] established that far-field earthquakes at low frequencies had greater impact on the structural performance compared to the near-field earthquakes at higher frequencies in the presence of the vertical ground motion. Simplified procedures were proposed by Collier and Elnashai [7] and Bozorgnia and Campbell [8] for combining the vertical and horizontal earthquake motions. Collier and Elnashai [7] established the distance limits of a structure to the earthquake source for the vertical ground motion to affect the structural performance. Wilson et al. [9] underscored the need for considering the vertical ground motion in the seismic analysis and design of horizontally skewed and curved bridges, particularly at moderate-to-high seismic zones. Jeon et al. [10] established that the varying axial force in highway bridges due to the vertical ground motion significantly increased the risk of damage in the bridges. Kim and Kim [11] and Ghaffarzadeh and Nazeri [12] found out that the vertical ground motion increased the horizontal spectral displacement of a structure, particularly if the structure was located in the near fault zone and the vertical-to-horizontal peak acceleration was high. Various structural codes [13-18] include the vertical ground motion to the design and analysis of structures by factoring the horizontal ground motion by a certain multiplier, based on the studies of previous researchers [2, 6, 8]. For instance, the Turkish Earthquake Code [16] recommends a value of 2/3 for this multiplier. Nevertheless, using a constant value for this multiplier can yield to inaccurate and non-conservative estimates, since the influence of the vertical ground motion can be much higher than this ratio depending on the V/H ratio, particularly when the structure is close to the source of the ground motion.

All these aforementioned studies underscored the need for the inclusion of the vertical component of the ground motion, particularly when the ratio of the vertical peak acceleration to the horizontal peak acceleration (V/H) and earthquake duration are high. The present study pertains to the investigation of the influence of varying V/H ratio and earthquake duration on the performance of the structure. For this purpose, an R/C structure was subjected to three different ground motions with varying V/H ratio and non-linear time history analyses were conducted. The damage states in the structural system under these ground motions were determined, which uncovered the effects of V/H ratio on the seismic behavior of structures.

2. Earthquake Ground Motions

P-waves (primary wave) are considered to be the source of the vertical component of earthquake motion whereas the horizontal component is directly related to S-waves (secondary wave), which means that the frequency content of the vertical component is higher than that of the horizontal component. Moreover, structure is first induced with the vertical component due to its shorter arrival time than the horizontal components. In case that structure has natural dominant frequency/period of vertical mode close to the vertical component of earthquake, the effect of this motion becomes much more important. One of the most significant parameter for damage indicator is the maximum acceleration of earthquakes. In this study, therefore, the V (vertical) /H (horizontal) ratio was considered in the earthquake motion selection for the time-history analyses. In addition, near-fault effect was taken into account in this selection. Based on these specifications, Imperial Valley (1979), Kobe (1995) and Kocaeli (1999) earthquakes were selected for earthquake analysis of the high-rise R/C structure. More details are given in Table 1. As shown from Table 1, the considered earthquakes have varying V/H ratios from Imperial Valley (1979) and Kobe (1995) to Kocaeli (1999). With the help of this variation, a comparative study was also conducted to indicate the effect of the different earthquakes on damage level of the R/C structure. The earthquake ground motions to be used in the non-linear time-history analyses are presented in Fig. 1. Data processes of detrending and base-line correction was also performed to make the earthquake records more reliable.

Table 1 – Specifications of the earthquakes

Year	Earthquake	Station	PGA (g)			Time (sec)	V/H
			H_1	H_2	V		
1979	Imperial Valley	El Centro Array #6	0.45	0.44	1.90	39.08	4.31
1995	Kobe	Port Island	0.35	0.29	0.57	41.98	1.96
1999	Kocaeli	Gebze	0.26	0.14	0.19	27.99	0.73

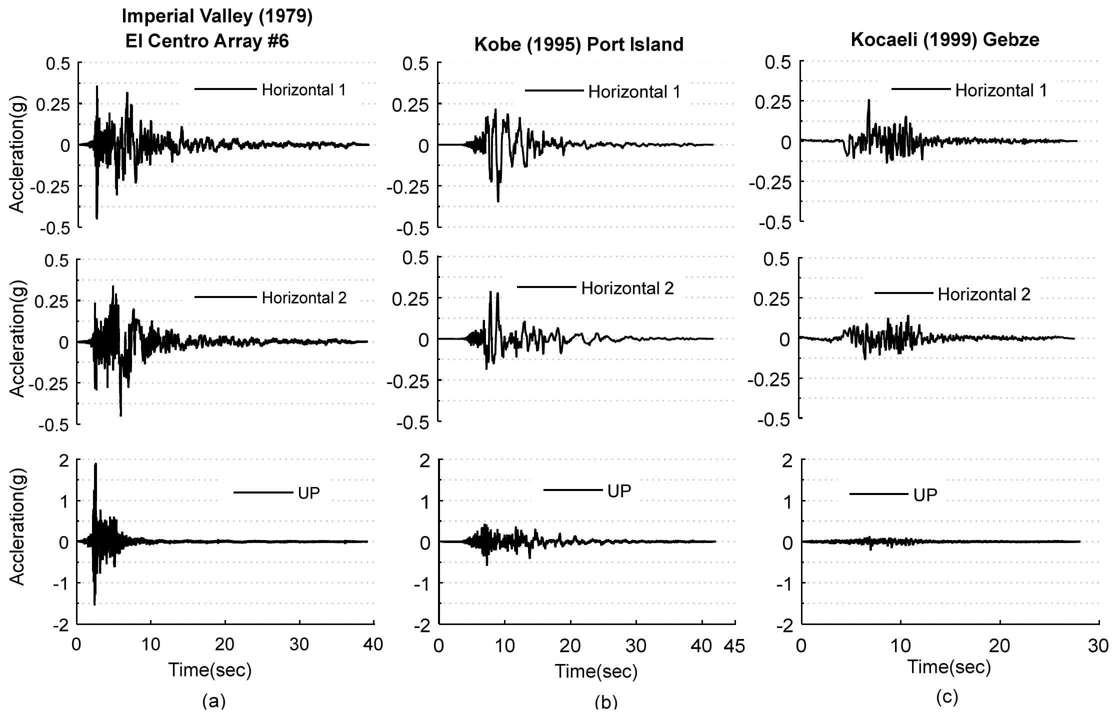


Fig. 1 – Earthquake ground motions

3. Finite Element Modeling and Modal Analysis of the R/C Structure

3.1 General features of the structure

The considered structure is an in-service existing R/C building. The requirements of the Turkish Earthquake Code (TEC-2007) [16] were used in the design of the structure with semi-ductile frame system of shear-wall-frame. Mat foundation system was considered and all stories of the structure have the same plan. The floor plan is indicated in Fig. 2. The general features of the structure are summarized in Table 2.

Table 2 – General properties of the structure

Number of story	10
Height of story (m)	4.5
Aim of structure	Municipality
Structural system	Shea-wall-frame (R=7)
Concrete class	C35 (f_{ck}=30 MPa)
Reinforcement class	S420 (f_{yk}=420 MPa)
Live load participation factor, n	0.3
Seismic zone	1st (A_0=0.4)
Importance factor (I)	1.5
Local site class	Z3, (T_a=0.15 s, T_b=0.60 s)

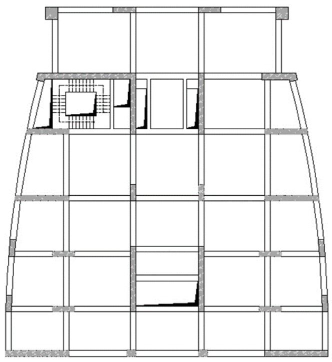


Fig. 2 – Floor plan

3.2 Finite element modeling

The efforts to establish a 3-D FE model of the R/C building were realized with the help of the SAP2000 [19] FE program. 3-D frame elements were utilized for beams and columns including reinforcement. Shear-walls were modeled thin shell elements. This element was also considered for the slabs. Due to its higher rigidity, the mat foundation was not included in the FE model. Instead of the foundation, the structure was supported at the base with the fixed restraints. Rigid diaphragm constraints were also assigned to the slab elements so as to safely transfer the earthquake load to structural system. The developed FE model is shown in Fig. 3. Material nonlinearity was defined in terms of the moment-curvature properties of the elements, especially beams, columns and shear-walls. Moment-curvature relations of all structural elements were obtained using the Xtract [20] section analysis program as indicated in Fig. 4a. Based on these considerations, plastic-hinge specifications were easily defined for each element, and then plastic-hinge was assigned to each structural element to SAP2000 as shown in Fig. 4b.

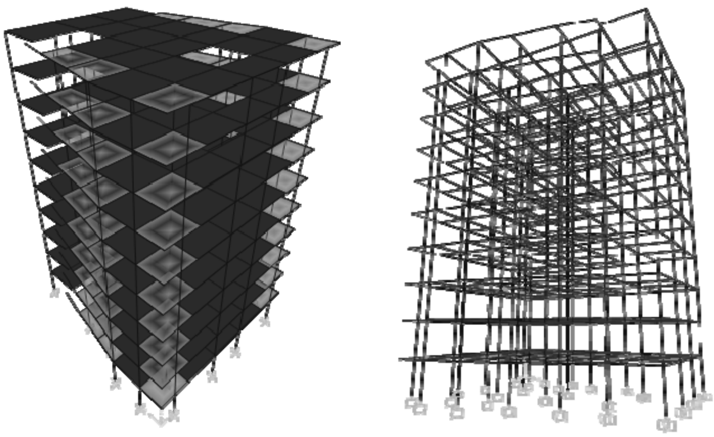
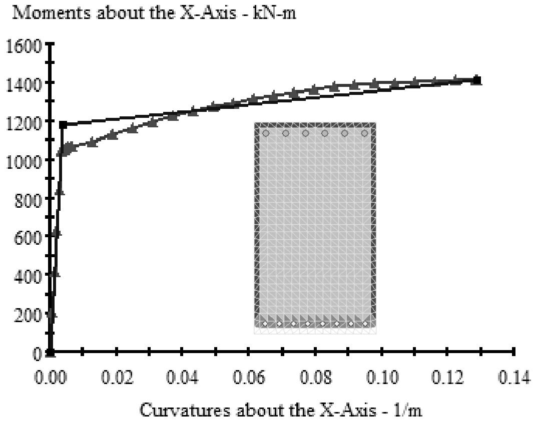
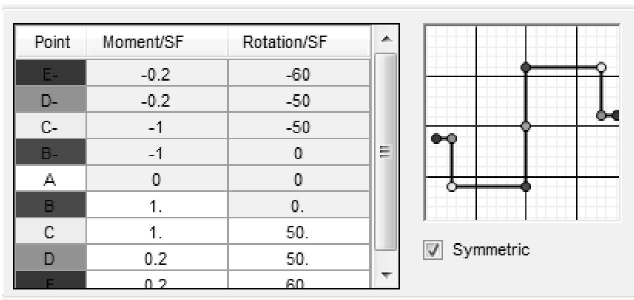


Fig. 3 – FE model of the R/C structure



(a)



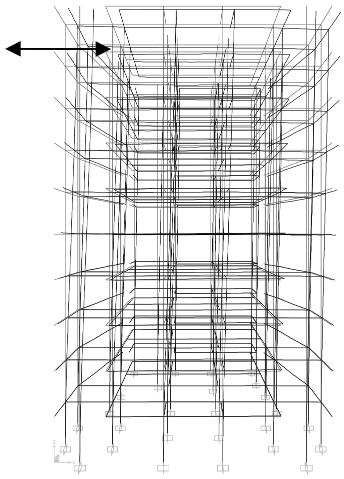
Point	Moment/SF	Rotation/SF
E-	-0.2	-60
D-	-0.2	-50
C-	-1	-50
B-	-1	0
A	0	0
B	1.	0.
C	1.	50.
D	0.2	50.
E	0.2	60

(b)

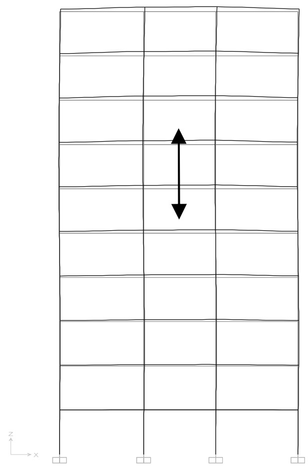
Fig. 4 – (a) Moment-curvature (b) Plastic- hinge assignment

3.3 Dynamic analysis

Based on the considerations for establishing numerical model of the R/C structure, the modal analysis was conducted to verify the correction of these considerations. Comparing the dominant frequency of the vertical component of the earthquakes with natural dominant frequency of the structure in vertical direction was also aimed. As indicated in Fig. 5a, the first mode shape and associated frequency were obtained in horizontal direction and as the value of 1.41 s^{-1}, respectively. The frequency of the vertical dominant mode of the structure was determined as 10.84 s^{-1}given in Fig. 5b.



(a)



(b)

Fig. 5 – Mode shapes: (a) Horizontal (b) Vertical

4. Linear and Non-Linear Time-History Analyses of the Structure

4.1 Linear time-history analysis

Linear time-history analyses were conducted previously and certain specific response indicators of the base

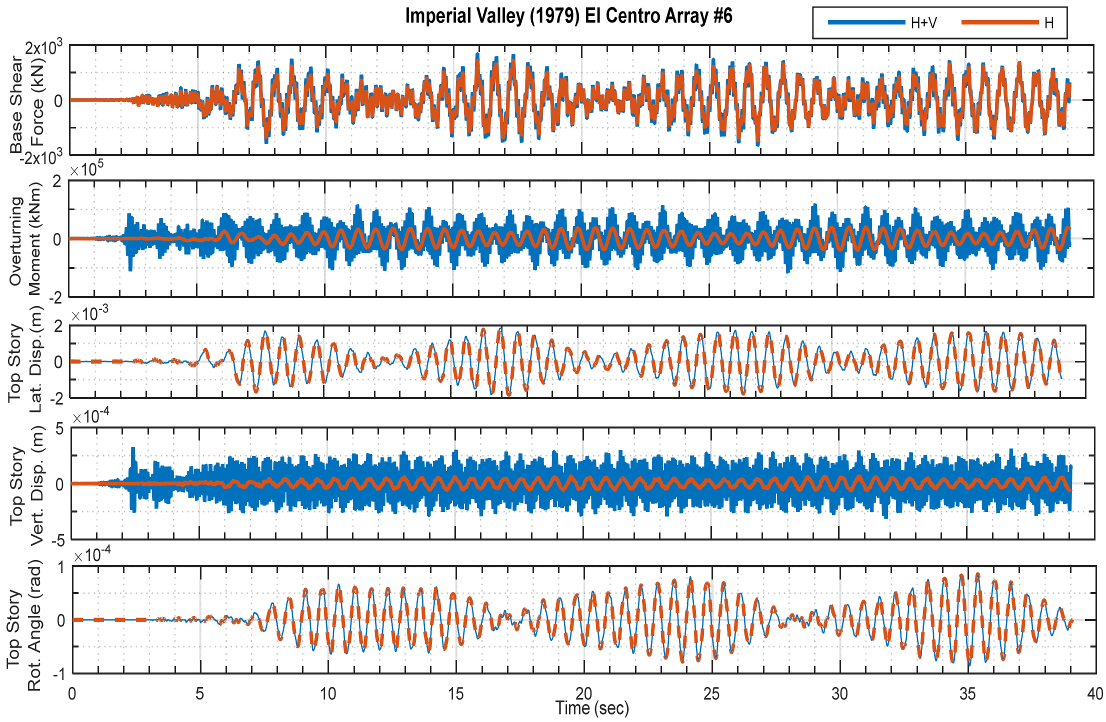


Fig. 6 – The results from Imperial Valley (1979)

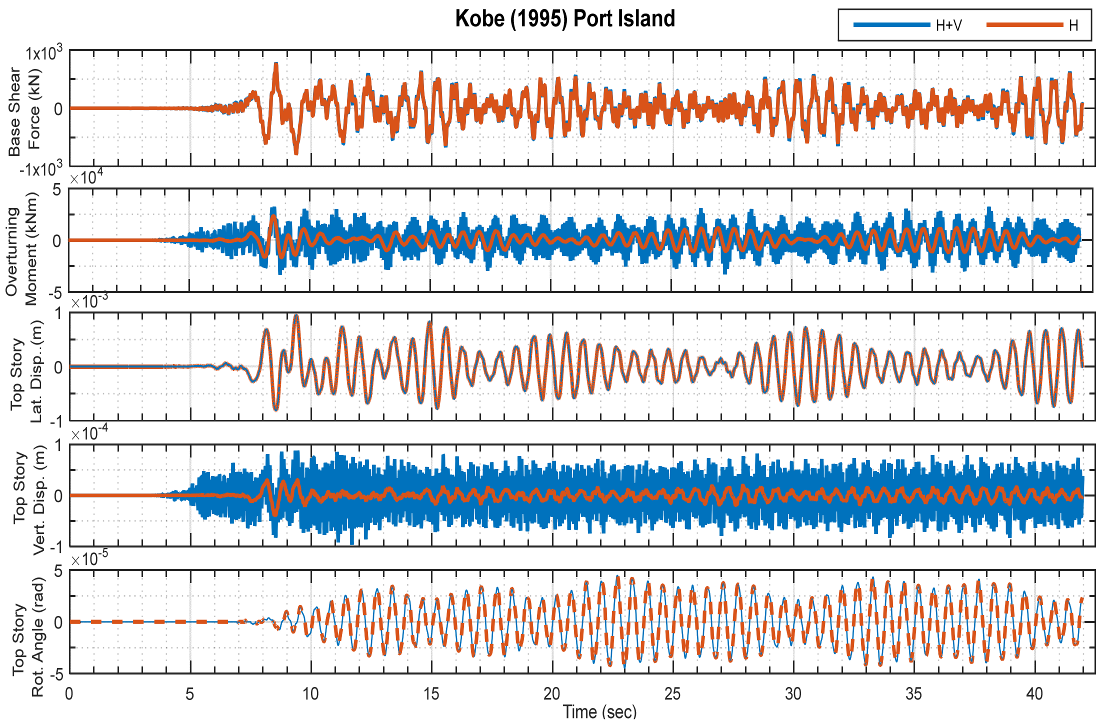


Fig. 7 – The results from Kobe (1995)

force, the overturning moment, the top-story lateral displacement, the top-story vertical displacement and the top-story rotation angle were determined to estimate the vulnerability of the structures under the vertical earthquake motion. These linear time-history analyses were conducted as the first stage of the present research. In this first stage, the structure was first subjected to two horizontal components of the earthquakes named as (H) and then the analysis was carried out again considering the vertical component named as (H+V). With the help of the obtained quantitative difference between the two load cases, the effects of the vertical earthquake motion were easily estimated.

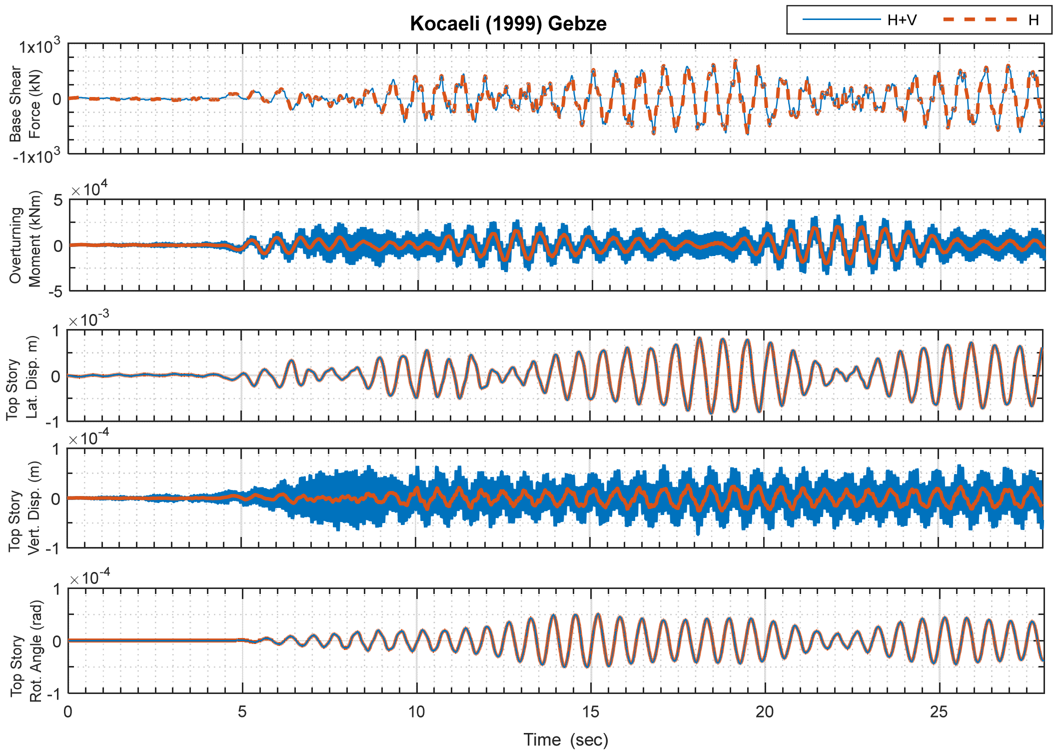


Fig. 8 – The results from Kocaeli (1999)

As shown in Fig. 6-8, the overturning moment and the top-story vertical displacement increased considerably for all earthquakes under the vertical earthquake motion compared to the other parameters. Actually, the base shear force also increased; however, this increase was lower than the increases in the overturning moment and the top-story vertical displacement values. The increases in these measures were primarily dependent on the V/H ratio of the earthquake record. The Imperial Valley (1979) earthquake with a higher V/H ratio given in Table 1 had greater effects on the structure than the Kobe (1995) and Kocaeli (1999) earthquakes. Therefore, the V/H ratio was determined to be one of the most important factors. The increase in the top-story vertical displacement in the earthquakes is another important outcome of the study, which shows that the rigid-diaphragm feature of the slab can be lost in the presence of the vertical component of a ground motion as a result of the out-of-plane deformations of the slab.

As a consequence, the high increase in the overturning moment is predicted to cause changes in the earthquake performance of the structural elements, particularly the shear-walls and the columns. The base shear force also contributes to this change; nonetheless, it can be ignored due to lower increase than the overturning moment.

4.2 Non-linear time-history analysis

In order to determine the earthquake performance level of the structural elements of the R/C building, the non-linear time-history analysis was conducted and performance levels were determined for each earthquake. For this aim, the provisions of the ASCE/SEI 41-13 [22] code were taken into account. This code proposes four performance levels of Elastic (EL), Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP) and Failure (F).

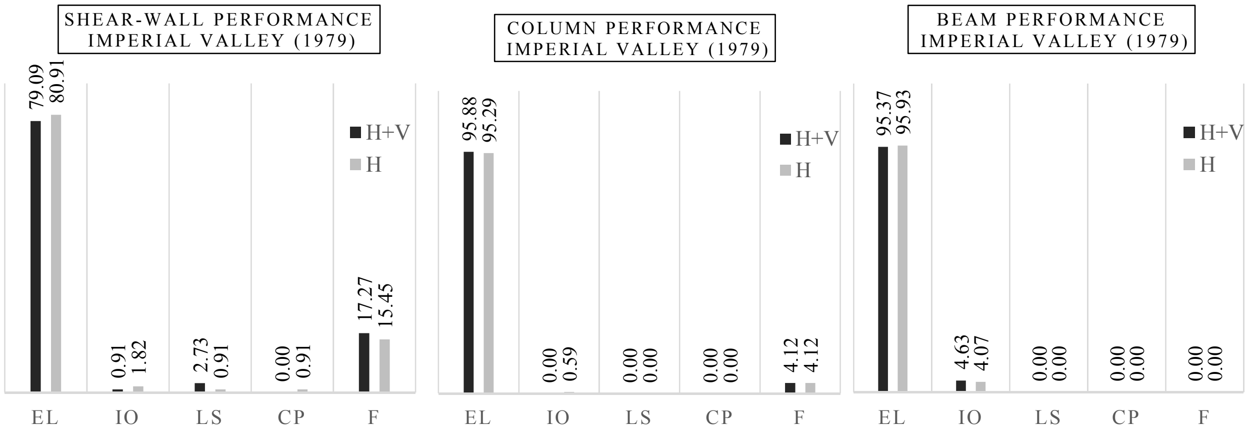


Fig. 9 – Performance levels of the structural element under Imperial Valley (1979)

Based on the results from the defined plastic-hinges for the beams, the columns and the shear-walls at the ends, the performance levels of these elements were determined. The performance levels of the members (beams, columns and shear walls) for the two ground motions are illustrated in Figs. 9-10. These two figures indicate that Failure (F) performance percentage increased as 2.0 % and 10.0 % for the shear-walls in Imperial Valley (1979) and Kobe (1995) earthquakes, respectively. The performance levels of the columns did barely change in the Imperial Valley (1979) earthquake, while decreasing by 2 % in the Kobe (1995) earthquake. The significant changes in the performance levels of the shear walls indicate that the changes in the structural response with the incorporation of the vertical component originates from the greater contribution of the shear walls to the structural response in the presence of the vertical component. Owing to high percentage of Failure (F) performance, the shear-walls can be concluded to bear a considerable part of changes in the earthquake load. This led to more ductile performance of the columns with less seismic load, which means less Failure (F) percentage under H+V loading case than that under H loading case. Moreover, the beams showed the same performance under the both load cases in the Imperial Valley (1979) and Kobe (1995) earthquakes. However, the percentage of Life Safety (LS) increased by approximately 6 % and Elastic performance (EL)

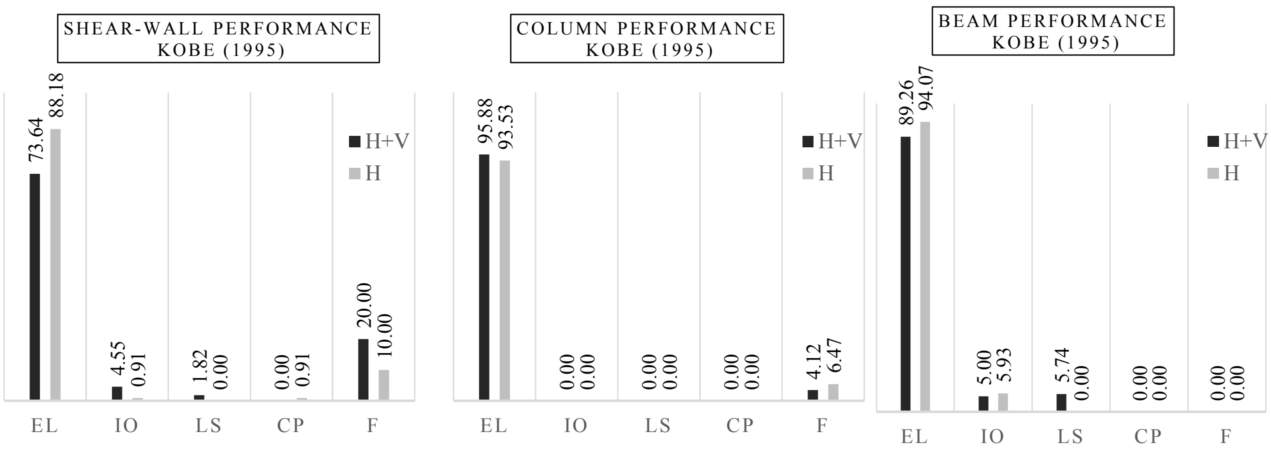


Fig. 10 – Performance levels of the structural element under Kobe (1995)

decreased under H+V loading case. Therefore, the beam elements generally were not influenced from the presence of the vertical earthquake motion. The relatively unchanged performances of the beams in both loading scenarios can be attributed to the fact that the changes in the forces and moments of the system with the incorporation of the vertical ground motion into the analyses are compensated by the increased performances of the shear walls, particularly at the failure level. In the Kobe (1995) earthquake, the high increase (10 %) in the failure performance (F) of the shear-walls (Fig. 10) resulted in the increase in the Life Safety (LS) performance of the beams. Similarly, the performances of the beams did barely change in the Imperial Valley (1979) earthquake due to slight increase (2 %) in the Failure performance (F) of the shear-walls. In Kocaeli (1999) earthquake, all structural elements showed nearly the same performance under both loading cases of the earthquakes. These results clearly indicate that the vertical component of a ground motion should definitely be accounted for in the design of the shear walls. This component can be ignored in the design of the beams and columns, since the inclusion of the vertical component is directly resisted by the shear walls.

5. Conclusions

The influence of the ratio of the vertical peak acceleration to the horizontal peak acceleration (V/H) of the ground motion on the seismic behavior of structures and damage states of structural members were investigated in the present study. The linear and non-linear time-history analyses were conducted on a structure for three different ground motions with varying V/H ratio. These analyses yielded to the following conclusions:

- The linear time-history analysis showed that the overturning moment and the base shear force could be considered as important indicator to estimate the performance level of the structural elements. Therefore, prior to performing detailed analysis, this analysis can be easily and fast conducted to understand how to behave under the vertical earthquake motion.
- From the non-linear analysis, the vertical load-bearing members of the shear-walls and the columns were shown to be influenced more than the beams. Especially, the shear-walls were damaged more than the columns. This finding was related to higher rigidity of the shear-walls than the columns.
- The performances of the beam elements were not affected from the vertical earthquake motion. However, their performances were determined to be changed based on the performance of the shear-walls and the columns.
- In addition to the V/H ratio, the duration of the earthquake was also obtained to be significant parameter, especially for the non-linear analysis. As given in Fig. 9 and Fig. 10, Failure (F) performance percentage was obtained higher under Kobe (1995) than under Imperial Valley (1979) although Imperial Valley (1979) had a higher V/H ratio than Kobe (1995). Thus, earthquake duration was concluded to have great effect on the performance of the structure.
- No changes in the performance of the elements were obtained under Kocaeli (1995) with the lowest V/H ratio and duration in the earthquakes. This conclusion demonstrated that the V/H lower than 1 had no effect on the performance of the structure. In the ground motions with V/H ratios much greater than unity, i.e. the Imperial Valley (1979) earthquake with a V/H ratio of 4.31 and the Kobe (1995) earthquake with a V/H ratio of 1.96, the inclusion of the vertical component caused rather significant increase in the vertical top deflection and base overturning moment values of the structures.

This study showed that the vertical ground motion plays an important role in the damage states and performances of particularly the vertical load-bearing members of a structure, i.e. the shear-walls and the columns. The performances and the damage states of the beams are much less affected from the magnitude and duration of the vertical component of a ground motion. Accordingly, the negative influence of the vertical component should be considered in the design of the vertical elements of a structural system.

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