16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2639

Registration Code: S-G1465969084

SEISMIC ASSESSMENT OF THREE-STORY RC FRAMES CONSIDERING VERTICAL-TO-HORIZONTAL PEAK ACCELERATION RATIO

S.Y. Kim[(1)], S.J. Kim[(2)], C.H. Chang[(3)], and Y.W. Jung[(4)]

[(1)] *Graduate Student, Department of Architectural Engineering, Keimyung University, Daegu, South Korea, kimsiyun1989@gmail.com*
[(2)] *Assistant Professor, Department of Architectural Engineering, Keimyung University, Daegu, South Korea, sjkim4@kmu.ac.kr*
[(3)] *Associate Professor, Department of Civil Engineering, Keimyung University, Daegu, South Korea, changclint@gmail.com*
[(4)] *Assistant.Prof, Dept. of Civil Engineering, Keimyung University, Daegu, South Korea, jyw@kmu.ac.kr*

Abstract

The paper presents an analytical assessment focusing on the effect of vertical ground motion on three-story RC frames with different geometric configurations. The selected 13 RC structures are designed to Korean Building Code 2009 by considering the different geometric configurations. The earthquake ground motions from nine stations are selected and the original records are manipulated with appropriate scale factor to match with seismic hazard in Korea. The effects of a suite of earthquake ground motion records with various vertical-to-horizontal peak acceleration ratios on RC frames are evaluated through nonlinear time history analyses. Analytical results are compared with the case of horizontal-only excitation. The analysis results from RC frames with different geometric configurations are also discussed. The effect of the vertical earthquake component on damage are taken into account. The structural response of RC frames is investigated at both the global and the local levels. Interstory drift is considered as a global failure criterion, while the effect of vertical ground motion on axial force, shear demand, and shear capacity of structural members is investigated. It is observed that the inclusion of the vertical component of ground motion significantly affected the response of RC frames. It is therefore concluded that vertical ground motion needs to be included in analysis for assessment and design.

Keywords: Vertical Ground Motion; Shear Capacity; V/H Ratio; RC Frame; Seismic Design

1. Introduction

Field observations from recent moderate-to-large magnitude earthquakes including Northridge earthquake (1994) in California, USA, Hyogo-ken earthquake (1995) in Kobe, Japan, Yojakarta earthquake (2006), Indonesia, Christchurch earthquake (2011), New Zealand reported that vertical component of strong ground motion caused the significant damage to RC structures. Furthermore, many of recent studies have confirmed the possible destructive effect of vertical ground motion on RC structures and thus its significance has gradually become of concern in the structural earthquake engineering community.

Mwafy and Elnashai (2006) evaluated the effect of the vertical ground motion on 12 RC buildings and indicated that interstory drift of collapse limit state was frequently reached when the effect of vertical ground motion was included. The study also showed that the axial compressive force and the curvature ductility demand in columns increased by up to 45% and 58%, respectively. Kunnath et al. (2008) examined the seismic performance of two-span highway bridges with six different structural configurations and found that significant increase in the axial force demand in the columns and moment demands in the girder. Hosseinzadeh (2008) investigated the seismic response of a simple RC bridge pier before and after retrofitting considering both horizontal and vertical ground motions. This analytical study indicated that the maximum axial force, bending moment, and shear force demand of the pier increased by about 30%, 10%, and 15%, respectively, due to vertical ground motion. Kim et al. (2011a) evaluated the effects of vertical ground motion on bridge piers taking into account vertical-to-horizontal peak acceleration ratios. One of the notable findings in this study is that the shear capacity of the pier is reduced by 25% when vertical component of strong ground motion is included. Also, Kim et al. (2011b) confirmed experimentally the effect of vertical ground motion on RC columns by conducting hybrid simulations. During the first simulation, the bridge and pier were subjected to only horizontal excitation while during the second the bridge and pier were subjected to combined horizontal and vertical excitation. It was observed that the vertical ground motion significantly affects the axial force variation and spiral strain of the second specimen, which were increased by 98% and 200%, respectively, compared to those of the first specimen. Lee et al. (2012) performed a combined experimental and analytical study on the effects of vertical ground motion on the shear capacity in bridge columns. From the experimental study, considerable tensile force was induced in columns due to vertical ground motion, resulting in degradation of shear capacity. It was also concluded that shear strength models by the current design codes were insufficient to predict the observed shear damage due to the lack of considering in the axial force fluctuation induced by high frequency vertical motion

Many researches described above lead several design codes including Eurocode (EC8) and FEMA P-750 (2009) to suggest vertical spectra. However, most of studies have focused on a structure located at the high seismic area and thus most of design codes in the countries of moderate seismicity still do not account for the effect of vertical ground motion on the structure. The study considering various geometric configurations in the structure is also sparse. Hence, in this study three-story RC frames with different geometric configurations are designed to the design code in moderate seismic country. The effect of vertical ground motion on various RC frames is analytically investigated taking into account various vertical-to-horizontal peak ground acceleration (V/H) ratios.

2. Selected RC Frames

The simple three-story RC frames with different geometric configurations shown in Fig. 1 are selected and designed to Korean Building Code (KBC 2009). As detailed in Table 1, the considered structural configurations are i) 5-equal spans with each length varying from 4m to 8m, ii) 5-differnet ratios of the interior span length (L2) to the exterior span length (L1) varying from 0.57 to 1.60, and iii) 5-different the column heights in the first story which are from 3.6m to 4.8m. It should be noted that the RC frames of SL6, SR100, and SH100 shown in Table 1 are identical and selected as a reference structure and thus a total of 13 structures is designed and considered.

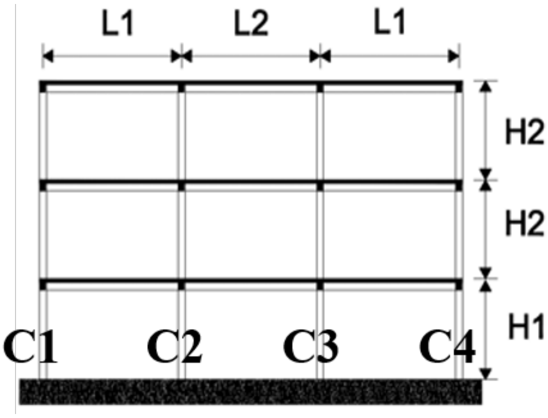


Fig. 1 – Elevation of RC Buildings

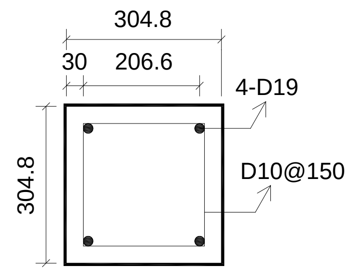


Fig.2 – Typical column section (unit: mm)

Table 1 – Details and Limit States of the RC Buildings

Case Name	Span Length (m)		Span Ratio	Story Height (m)		Story Height Ratio	Natural Period (sec)	Limit State [Interstory Drift Ratio (%)]		
	L1	L2	L2/L1	H1	H2	H2/H1		Serviceability	Damage Control	Collapse Prevention
Span Length										
SL4	4.00	4.00	1.00	3.60	3.60	1.00	0.77	0.83	1.71	2.45
SL5	5.00	5.00	1.00	3.60	3.60	1.00	0.89	0.84	1.32	1.96
SL6	6.00	6.00	1.00	3.60	3.60	1.00	0.99	0.85	1.18	1.78
SL7	7.00	7.00	1.00	3.60	3.60	1.00	1.09	0.83	1.12	1.72
SL8	8.00	8.00	1.00	3.60	3.60	1.00	1.19	0.79	1.13	1.94
Span Ratio										
SR057	7.00	4.00	0.57	3.60	3.60	1.00	1.02	0.83	1.37	1.99
SR077	6.50	5.00	0.77	3.60	3.60	1.00	1.00	0.84	1.22	1.88
SR100	6.00	6.00	1.00	3.60	3.60	1.00	0.99	0.85	1.18	1.78
SR127	5.50	7.00	1.27	3.60	3.60	1.00	0.98	0.85	1.16	1.76
SR160	5.00	8.00	1.60	3.60	3.60	1.00	0.96	0.84	1.07	1.74
Story Height										
SH075	6.00	6.00	1.00	4.80	3.60	0.75	1.26	1.04	1.48	1.99
SH080	6.00	6.00	1.00	4.50	3.60	0.80	1.18	0.99	1.41	1.93
SH086	6.00	6.00	1.00	4.20	3.60	0.86	1.11	0.95	1.33	1.88
SH092	6.00	6.00	1.00	3.90	3.60	0.92	1.05	0.90	1.26	1.82
SH100	6.00	6.00	1.00	3.60	3.60	1.00	0.99	0.85	1.18	1.78

The concrete compressive strength of 24 MPa and rebar yielding strength of 400 MPa are used for all materials. Fig. 2 shows the details of column section in the reference structure. The cross section of the column is 304.8mm × 304.8mm with four longitudinal reinforcement with the diameter of 19.1mm. The stirrup with the diameter of 9.53 mm is used with a spacing of 150 mm throughout the length. The Mid-America Earthquake Center program Zeus-NL was utilized to perform the analyses for the selected structures. Zeus-NL is an inelastic fiber analysis package which was specifically developed for earthquake engineering applications (Elnashai et al., 2004). The fundamental period of each structure from eigenvalue analysis is shown in table 1 and has a tendency to increase as span length and story height increase due to increase in mass and decrease in lateral stiffness.

3. Limit States and Response Measure

Structural damage or failure may occur due to the attainment of member or system level limit states. Thus, in this study the structural response through nonlinear time history analysis is investigated at both the global and the local levels. Interstory drift is considered as a global failure criterion, while the axial force variation and shear capacity of structural members are monitored to assess failure on a local level.

Interstory drift limit per each individual structure from pushover analysis with loading profile of first mode shape is estimated and three limit states termed 'serviceability', 'damage control', and 'collapse prevention' are used (Kwon and Elnashai, 2006). The limit states are defined as followings; i) serviceability is defined when longitudinal rebar reach the yielding, ii) damage control is defined when concrete strain reaches the maximum confined stress, iii) collapse prevention is defined when concrete strain reaches the ultimate confined strain(ϵ_{cu}) that was defined EC8. The maximum strain (ϵ_{cu}) can be calculated as shown in Eq. (1) and Eq. (2);

$$\varepsilon_{cu} = 0.0035 + 0.1\alpha\omega_w \tag{1}$$

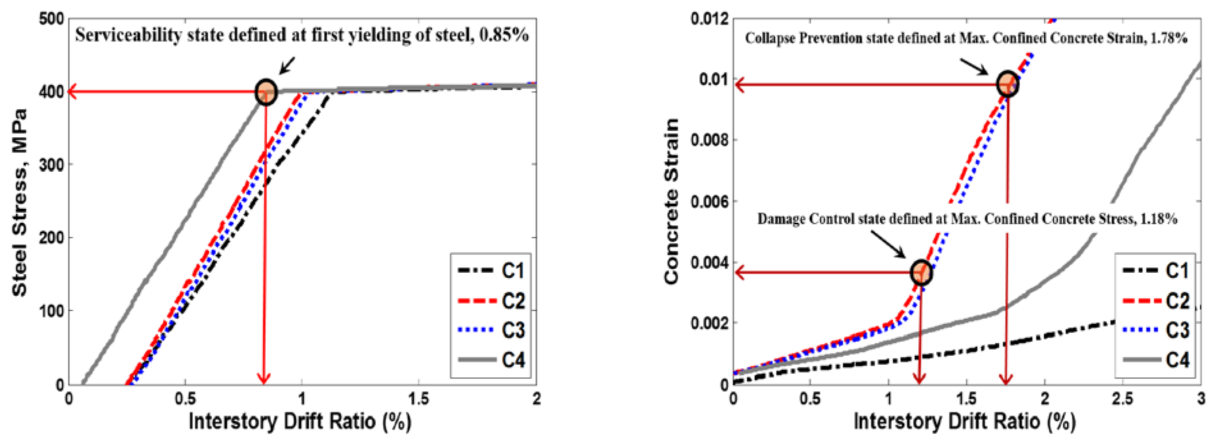
$$\alpha = \left(1 - \frac{\sum \omega_i^2 / 6}{A_{cc}}\right)\left(1 - \frac{s}{2d_c}\right)^2 \tag{2}$$

Where, ω_w is volumetric ratio of confined hoop, α is confinement effectiveness coefficients, ω_i is i th clear distance between adjacent longitudinal bars, A_{cc} is area of concrete core, d_c is core dimensions to centerlines of perimeter hoop. As shown in Fig. 3, responses of the internal and external columns (C1 to C4 shown in Fig. 1) at the first story are monitored in order to determine the limit states. The first story drifts corresponding to each limit state for SL6 frame are 0.85%, 1.18%, and 1.78%. It is assumed that these limit states can be also applicable to the remaining stories. Table 1 summarizes each limit state per structure and its fundamental period.

To investigate the effect of vertical ground motion on the local level, axial force variation on columns in the first story is assessed. The effect of vertical ground motion on axial force variation is evaluated by considering the ratio of axial force variation induced by the only vertical excitation to gravity load as shown in Eq. (3).

$$\frac{AFV_{H+VGM} - AFV_{HGM}}{Gravity\ Load} \times 100 \tag{3}$$

Where, AFV is the axial force variation which is defined as the difference between maximum and minimum axial forces on column during the simulation.



(a) Serviceability (b) Damage Control and Collapse Prevention

Fig. 3 – Limit States of SL6 Frame

Including shear as a failure criterion is also investigated in terms of shear demand and capacity of columns at the first story. To consider the shear capacity, shear strength models by ACI318-14, Priestley et al. (1994), Sezen and Moehle (2004), and Pan and Li (2013) are employed. The model proposed by Priestley et al. (1994) is composed of three independent components; concrete contribution considering displacement or curvature ductility, shear reinforcement contribution based on the truss mechanism using a 30^{o} angle of inclined shear cracking, and shear resistance of the arch mechanism provided by axial force. Sezen and Moehle (2004) also proposed the shear strength model including contributions from the concrete and transverse reinforcement by considering the column cross-sectional dimensions, concrete compressive strength, column aspect ratio, axial load, and displacement ductility demand. On the basis of the truss-arch model, Pan and Li (2013) proposed the shear strength model which considers both the contributions of concrete and transverse reinforcement to shear strength in the truss model, as well as the contribution of arch action through compatibility of deformation. More details can be found in each reference.

4. Selection of Strong Ground Motion

Earthquake ground motion records from PEER NGA database were selected to evaluate to effect on vertical ground motion for RC buildings. Selection criteria is shown below:

- Earthquake magnitude(M_w) is more than 6.0
- Closest distance to the fault is less than 50km
- Peak ground acceleration (PGA) of horizontal ground motion is more than 0.2g
- Vertical-to-horizontal peak ground acceleration (V/H) ratio is more than 0.6
- Scale factor of earthquake ground motion record is between 0.75 and 1.25

As shown in Table 2, a total of nine records is selected for the analysis. Scale factor to each horizontal ground motion is applied to match to spectral acceleration value of the maximum considered earthquake (MCE) for the soil class (S_c) of KBC 2009 at the fundamental period (0.99sec) of a reference structure. Fig. 4 shows the response acceleration spectra with MCE spectrum from KBC 2009. In addition, as depicted in Fig. 5, vertical spectra proposed by EC8 are matched well with those of selected records.

Table 2 – Selected Ground Motions

Eearthquake	M_w	Station	Fault Dist. (km)	PGA(g) H	PGA(g) V	V/H	Scale Factor to HGM	Ref. Name
Imperial Valley (1979)	6.5	Chihuahua	7.3	0.270	0.218	0.807	1.22	IV-CHI
N. Palm Springs (1986)	6.0	Morongo Valley Fire	12.0	0.205	0.395	1.929	1.02	PS-MVH
Northridge (1994)	6.7	Arleta Fire	8.7	0.308	0.552	1.790	0.97	NO-ARL
		Canoga Park	14.7	0.356	0.489	1.374	1.09	NO-CNP
		N Faring Rd	20.8	0.242	0.191	0.186	0.96	NO-FAR
		Roscoe Blvd	10.1	0.303	0.306	1.010	0.97	NO-ROB
Chi-Chi, Taiwan (1999)	7.6	TCU055-NS	6.3	0.201	0.167	0.831	0.98	CC-TCN
		TCU089	9.0	0.248	0.191	0.774	1.08	CC-TCU
Kobe (1995)	6.9	Kobe Univ.	0.9	0.310	0.380	1.220	1.81	KB-KBU

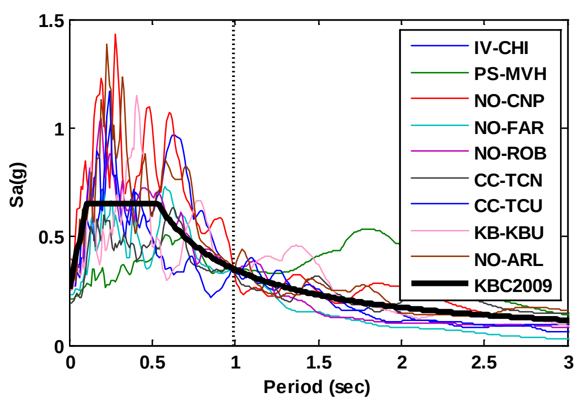


Fig. 4 – Horizontal Spectra

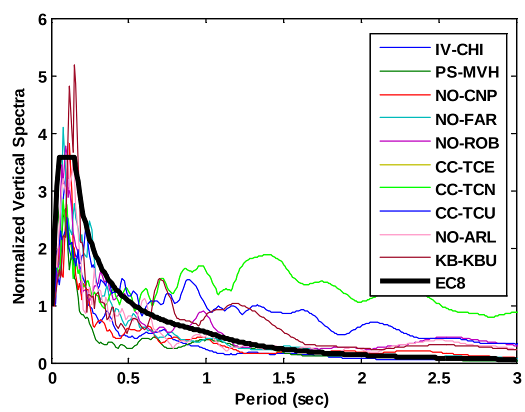


Fig. 5 – Normalized Vertical Spectra

5. Analysis Results

Nonlinear time history analyses with the selected 13 RC frames and nine ground motions are performed to investigate the effect of vertical ground motion. Kim et al. (2011a) showed the distribution of V/H ratio for 452 earthquake ground motion records and indicated that the V/H ratios for 97% of the ground motions is less than 2.0. Thus, for each structure and record, 16 V/H ratios for a fixed horizontal PGA are considered, which is in the range of from 0.5 to 2.0 with an increment of 0.1 in this study. Analytical results are compared with the case of horizontal-only excitation. On the global level, the interstory drift is monitored up to collapse prevention limit. The example of interstory drift distribution along the story of SL6 is shown in Fig. 6. Since P-Δ effects can be significant and could lead to instability of structures at values in excess of the collapse limit, member response in excess of the collapse prevention limit is not included for local levels.

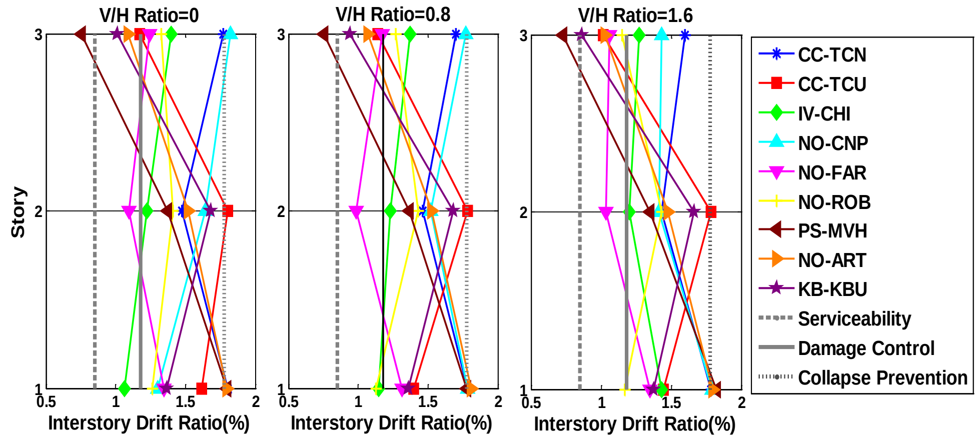
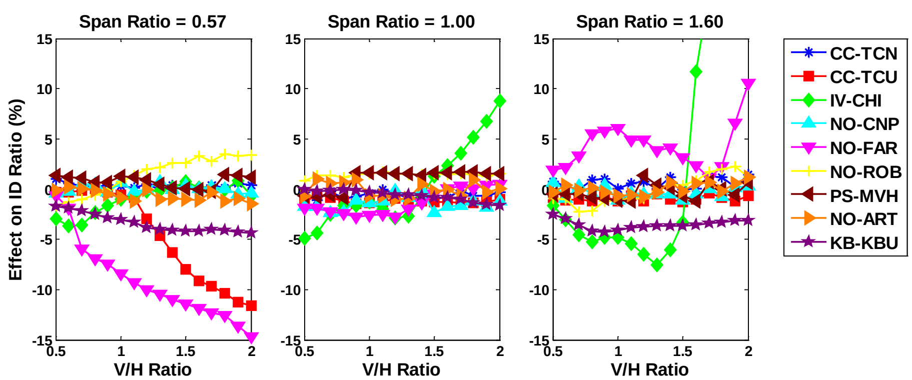
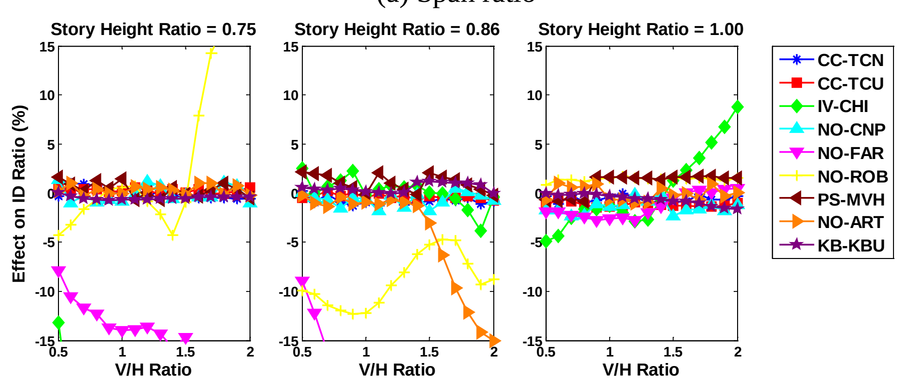


Fig. 6 – Interstory Drift Ratio, SL6



(a) Span ratio



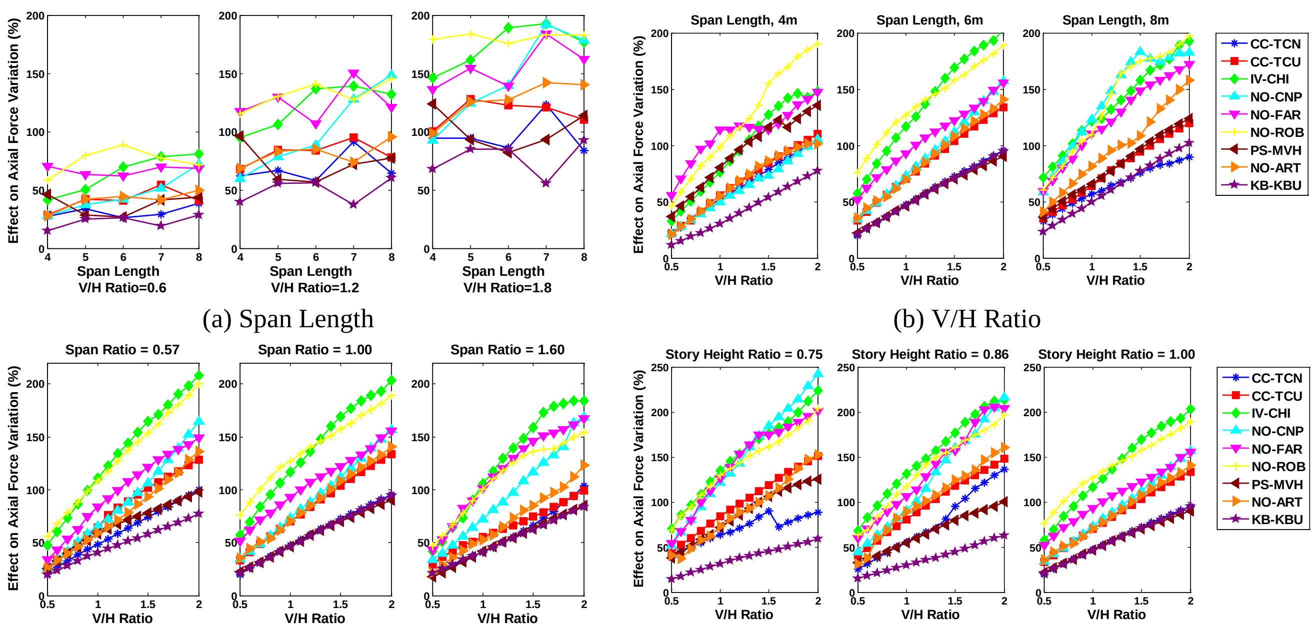
(b) Story height

Fig. 7 – Effect on Interstory Drift Ratio

Effect on the interstory drift ratio is evaluated for the RC frames with different geometric configuration. As depicted in Fig. 7, the change in the effect on the interstory drift ratio is observed to fluctuate as V/H ratio increases. For most of earthquake records the effect on the interstory drift ratio is within the range of +/- 3%. Although including vertical ground motion seems to have a minimal effect on the interstory drift ratio for most of records, interstory drift ratios in some records are significantly affected by vertical ground motion. For example, interstory drift ratio of the structure shown in Fig. 7 (a) increases up to 36% when vertical component of earthquake records is considered.

Fig. 8 shows that the effect of vertical ground motion on axial force variation. As illustrated in Fig. 8, the axial force variation on the first column is significantly affected by vertical ground motion as V/H ratio increases. Fig. 8 (a) indicates that the effect on axial force increases as span length increases. The axial force variations on columns in RC frames with different geometric configurations including span length, span ratio, and story height increase up to 205.93% (NO-ROB), 223.01% (IV-CHI), and 242.60% (NO-CNP), respectively. Note that the effect shown in Fig. 8 is the ratio of contribution of vertical ground motion to the axial force variation, normalized by the dead load as previously given by Eq (3).

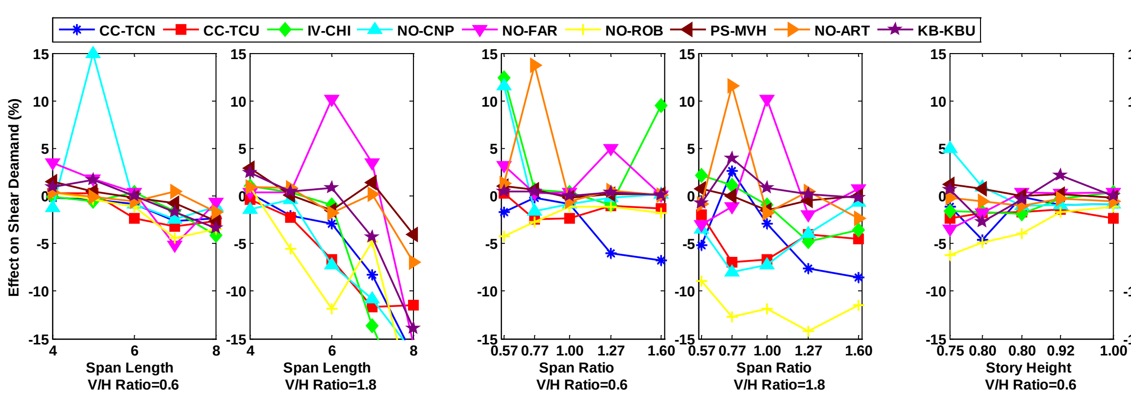
The significant variation of axial load discussed above also leads to fluctuations in column shear demand and capacity. Fig. 9 presents the effect of vertical ground motion on the shear demand of columns in RC frames with different span length, span ratio, and story height. As shown in Fig. 9, no clear correlation exists between the shear demand and V/H ratio. However, the effect on shear demand has a tendency to slightly decrease up to 15% as span length increases.



(a) Span Length (b) V/H Ratio

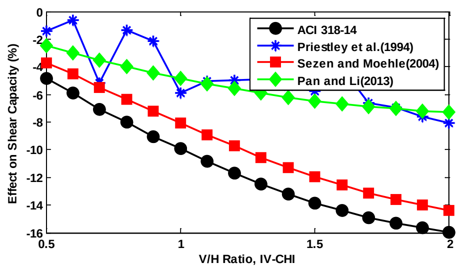
(c) Span Ratio (d) Story Height Ratio

Fig. 8 – Effect on Axial Force Variation

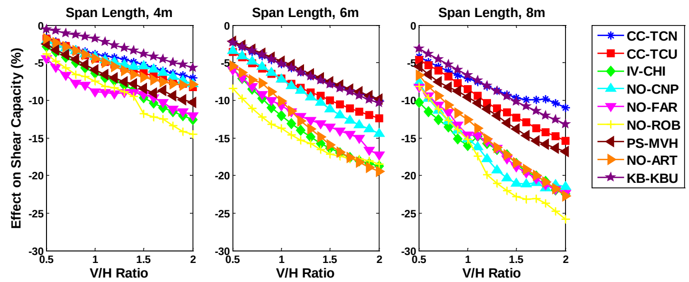


(a) Span length (b) Span ratio (c) Story height

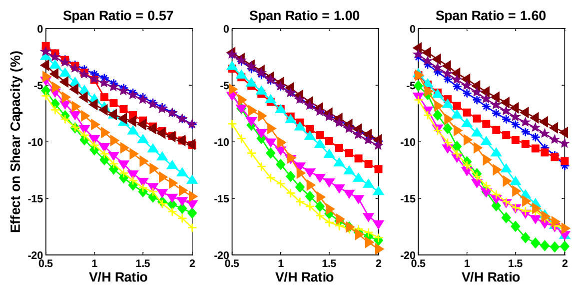
Fig. 9 – Effect on Shear Demand



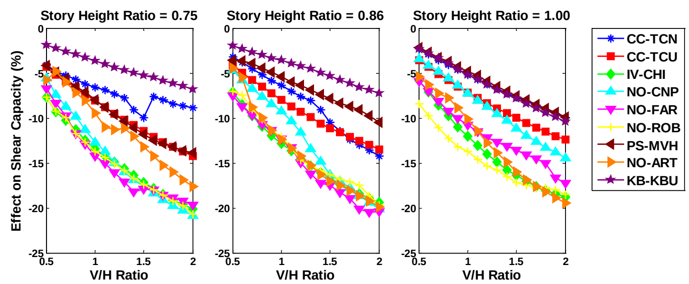
(a) Comparison of various approaches



(b) Span length



(c) Span ratio



(d) Story height

Fig. 10 – Effect on Shear Capacity

Concerning the shear capacity of the column, shear strength model by ACI 318-14 as well as the predictive approaches by Priestley et al. (1994), Sezen and Moehle (2004), and Pan and Li (2013) are utilized as shown in Fig. 10 (a). It should be noted that the effect on shear strength using the predictive approaches is currently under evaluation and thus this paper mainly focuses on approach of design code. Fig. 10 (b) to (d) show the clear trend in reduction of shear capacity. The shear capacity is reduced up to 25.8 % as vertical motion amplitude increases. The shear capacity also decreases as the span length and ratio increase. As previously mentioned, the effect of vertical ground motion on interstory drift ratio is minimal, while the effect on axial force variation is significant. Therefore, it is concluded that the axial force variation results in noteworthy reductions in shear capacity.

.

6. Conclusion

The paper presents the analytical assessment of the effect of vertical ground motion on RC frames with different span length, variable span ratio, and various column heights by considering various vertical-to-horizontal peak ground acceleration ratios. It is observed that effect of vertical ground motion on the interstory drift ratio of RC frames is minimal with the range of +/- 3% for most of selected records. However, the axial force variation on the column at the first story significantly increases up to about 240% when vertical component of earthquake ground motion is included. This significant effect on axial force leads to a noteworthy reduction in shear capacity up to 25.8% compared to the response with horizontal-only excitation. Thus, it could be concluded that the variation of axial force results in reduction in shear capacity of RC columns and increases the potential for shear failure. Therefore, the overall outcome of the analytical investigation discussed in this study is that in the vicinity of active faults, where V/H is likely to be high, shear capacity and demand assessment needs to take vertical ground motion into account.

7. Acknowledgements

The work presented in this paper was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2014R1A1A1006267 & 2014R1A2A1A11052469).

8. References

[1] Mwafy A, Elnashai AS (2006): Vulnerability of Code-Compliant RC Buildings under Multi-Axial Earthquake Loading. *4th International Conference on Earthquake Engineering*, Taipei, Taiwan.

[2] Kunnath SK, Erduran E, Yashinsky YH, Yashinsky M (2008): Effect of Near-Fault Vertical Ground Motions on Seismic Response of Highway Overcrossings. *Journal of Bridge Engineering*, **13**(3), 282-290.

[3] Hosseinzadeh N (2009): Vertical Component Effect of Earthquake in Seismic Performance of Reinforced Concrete Bridge Piers. *14th World Conference on Earthquake Engineering*, Beiging, China.

[4] Kim SJ, Holub CJ, Elnashai AS (2011a): Analytical assessment of the effect of vertical earthquake motion on RC bridge piers. *Journal of Structural Engineering*, **137**(2), 252-260.

[5] Kim SJ, Holub CJ, Elnashai AS (2011b): Experimental investigation of the behavior of RC bridge piers subjected to horizontal and vertical earthquake motion. *Engineering Structures*, **33**(7), 2221-2235.

[6] Lee H, Gunay MS, Mosalam KM, Kunnath SK (2012): Consequences of Strong Vertical Accelerations on Shear Demand and Capacity in Bridge Columns. *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[7] Eurocode 8 (2005): Design of structures for earthquake resistance-Part 1: General rules, seismic actions and rules for buildings. CEN European Committee for Standardisation, Brussels.

[8] FEMA P-750 (2009): NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. *Federal Emergency Management Agency*

[9] Korean Building Code (2009): KBC 2009. Architectural Institute of Korea, Seoul, Korea.

[10] Elnashai AS, Papanikolaou V, Lee D (2004): Zeus NL-A System for Inelastic Analysis of Structures. *Mid-America Earthquake Center*, CD Release 04-01.

[11] Kwon OS, Elnashai AS (2006): The effect of material and ground motion uncertainty on the seismic vulnerability curves of RC structure. *Engineering structures*, **28**(2), 289-303.

[12] ACI (2014): Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary. *American Concrete Institute*. Farmington Hills, MI, USA.

[13] Priestley MN, Verma R, Xiao Y (1994): Seismic shear strength of reinforced concrete columns. *Journal of structural engineering*, **120**(8), 2310-2329.

[14] Sezen H, Moehle JP (2004): Shear strength model for lightly reinforced concrete columns. *Journal of Structural Engineering*, **130**(11), 1692-1703.

[15] Pan Z, Li B (2013): Truss-arch model for shear strength of shear-critical reinforced concrete columns. *Journal of Structural Engineering*, **139**(4), 548-560.