EFFECT OF DISTRIBUTED MASS ON EARTHQUAKE RESPONSE OF REINFORCED CONCRETE FRAMES

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SUMMARY

This paper studies the effect of near field earthquakes on the response of reinforced concrete buildings with a special emphasis on the influence of vertical component of ground motions on nonlinear response of framed buildings with distributed lumped masses along girders. The vertical ground motion excites the vertical vibration of floor slabs. In conventional analyses, floor mass is assumed to concentrate at beam-column connections for simplicity. Thus, vertical vibration due to distributed masses along slabs and girders is neglected. This paper compares the response of the conventional lumped-mass model with the model incorporating distributed vertical masses along girders subjected to horizontal and vertical components of near field earthquakes. A computer program for the nonlinear earthquake response analysis of frames with distributed masses was developed. The comparison revealed that the horizontal story displacement and story shear responses were little affected by the vertical motion. On the other hand, the axial force of columns and the vertical displacement of girders are significantly influenced when a building is subjected to a large vertical ground motion. The effect of vertical motion on the axial force of columns was more critical when the contribution of lateral seismic load was small such as in a low-rise building or in the interior columns of an intermediate or high-rise building. It was also observed that the vertical vibration could cause more fluctuation in column axial forces, the intensity of which was found proportional to the intensity of vertical ground motion. Distributed mass under vertical motion can significantly change the size of axial force fluctuation in columns, and consequently the lumped mass model must be used conscientiously in estimation of column axial force. The contribution of distributed mass and vertical motion to the axial force in a frame column needs more studies.

INTRODUCTION

Design of a ductile frame dissipating seismic energy based on the concept of capacity design method [NZS-1982, NZS-1995, and AIJ-1990] is well accepted by engineers. One of the basic requirements of the method is to design a column with high degree of protection against yielding during severe earthquakes. The effect of vertical motion on the design axial forces in columns is not considered explicitly in the NZS and AIJ guidelines. When a building locates close to the epicenter and/or ruptured fault, it may simultaneously suffer non-attenuated horizontal and vertical components of a ground motion. The vertical peak ground acceleration (PGA) of an earthquake record may exceed the horizontal PGA. Moreover, in a near field region, the peak of vertical-to-horizontal spectral ratio is even larger than the ratio of the PGA, especially at short period spans [Bozorgnia and Niazi 1995]. On the other hand, vertical period of a building system/member is small and falls in a narrow range of 0.05 to 0.26 second [Anderson and Bertero 1974, Kikuchi and Yoshimura 1984, Bozorgnia and Niazi 1998], a period span which may correspond to a range of high vertical response spectra, particularly in near field regions. The effect of vertical motion to the column forces may not be negligible. This paper is an attempt to study the earthquake response characteristics of R/C frames located in a near-filed region.

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ANALYTICAL MODEL AND EARTHQUAKE MOTIONS

A computer program for nonlinear earthquake response analysis of R/C frames with distributed mass along girders was developed. Girders were divided into 10 segments along their axis and floor masses were lumped at the internal nodes and at the centerline of columns. One component model [Giberson 1967] was used for girder segments with symmetric moment distribution and for columns with assymetric moment distribution. The constant gravity loads were applied gradually as vertical concentrated forces at the centerline of columns and at the internal nodes along a girder within 100 loading steps prior to the real dynamic analysis. Only material nonlinearity was included, and the geometrical nonlinearity was assumed to be negligible. A trilinear skeleton curve was assumed for a moment-rotation relation at each member ends. The Sugano equation [Sugano 1970] was used to estimate the post cracking stiffness. The post-yielding stiffness was assumed equal to 1% and 5% of the initial stiffness for a girder-segment and a column, respectively. Axial stiffness was assumed to be linearly elastic. Beam-to-column joints were assumed to be rigid with a finite length equal to column or beam widths. The members were assumed to have infinite ductility, so that failure by attainment of the actual ultimate strength or deformation capacity of a member should not be considered. A viscous damping proportional to the mass matrix and instantaneous stiffness matrix was assumed. Damping was assumed equal to 0.05 in fundamental horizontal and vertical vibration modes. Twenty seconds of two near field strong ground motion records, the 1995, Kobe-JMA record and the 1994, Northridge-Saticoy record were used. Absolute acceleration response spectra of linearly elastic system with 0.05 damping subjected to the records are presented in Figure 1. The peak vertical response acceleration of Northridge-Saticoy record is larger than that of the horizontal response, and falls at a period of 0.10 second; while the peak vertical response acceleration of Kobe-JMA record is smaller than the horizontal response, and occurs at a period of 0.25 second.

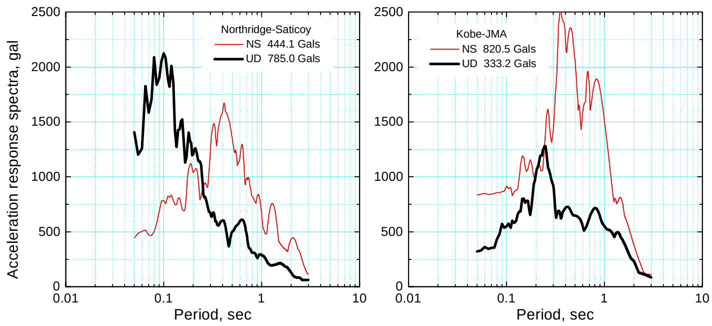


Figure 1: Acceleration response spectra of a linearly elastic system with 0.05 damping subjected to near field records used in this study

3. SINGLE-STORY ONE-BAY PROTOTYPE FRAMES

Five R/C plane frames with different span lengths of 4, 8, 12, 16, and 20 meters long were designed for a combination of dead load of 36 kN/m, live load of 12 kN/m, and seismic coefficient C_b of 0.2 (Fig. 2). Dimensions of frame members were determined for a reinforcement ratio of about 1%. Compressive strength of concrete and yielding strength of steel were 30 and 400 MPa; and modulus of elasticity of concrete and steel were 29.2 and 200 GPa, respectively. Member sections and natural period of frames are listed in Table 1. One half of live load was considered to be effective as inertia mass in the horizontal direction. Total dynamic weight of frames were 192, 384, 576, 768, and 960 kN for span lengths of 4, 8, 12, 16, and 20m, respectively. The analysis was carried out for different cases of frames subjected to (a) vertical motion alone, (b) horizontal motion alone, and (c) vertical and horizontal motions; with lumped mass model , and with distributed mass model.

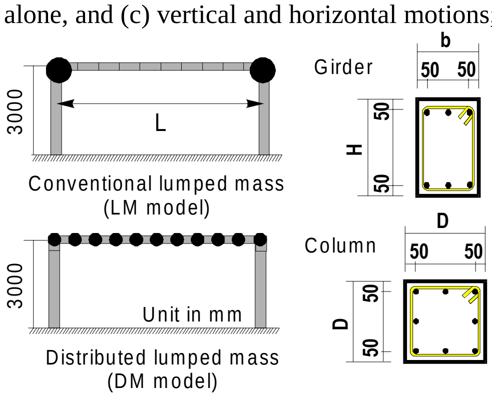


Figure 2: Analytical model and prototype structure

Table 1: Frame parameters and characteristics

L (m)	b (mm)	H (mm)	D (mm)	Natural periods (sec)	
				Horizontal	Vertical
4	300	400	350	0.16	0.06
8	400	550	500	0.13	0.11
12	500	700	650	0.11	0.14
16	500	700	800	0.12	0.22
20	500	700	900	0.08	0.36

Figure 3 compares the axial force of column in the frame with 4-meter bay subjected to horizontal and vertical (H + V) components of Northridge motion. The axial force is 17% larger in compressive side for distributed mass model (DM) than that of lumped mass model (LM). The ratios of maximum response axial forces to the initial design axial forces are illustrated in **Figure 4**. The contribution of horizontal motion to the axial force is small in long span frames. The axial forces ratio to the design load are increased about 50% and 75% under Kobe and Northridge ground motions, respectively. This indicates that the maximum axial forces are proportional to the magnitude of vertical motion. However, column axial forces in some frames are much affected by dynamic characteristics of the frame and vertical motion than that of magnitude of the vertical motion. The LM model may underestimate the column axial forces under some circumstances. The interaction response diagrams at the top of frame column are compared in Figure 5. The column seems to be much affected by change in the bending moment than fluctuation in axial force in interaction diagram of column (Fig. 5a). The effect of distributed mass and vertical motion can be observed in a close up view of the response in Figures 5b and 5c. Axial force in column is significantly increased by the vertical motion. Axial force and bending moment of column are further increased by the effect of DM model under vertical motion. The LM model, on the other hand, can not take into account the effect of vertical floor vibration to the bending moment. This can be concluded from upright shape of response interaction diagram of frame subjected to vertical motion alone in Figure 5b. It can be seen from Figure 5c that the column may yield by the combination effects of vertical motion and distributed mass.

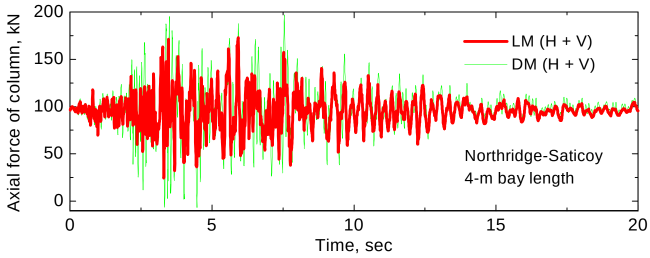


Figure 3: Axial force in column of frame with 4m bay

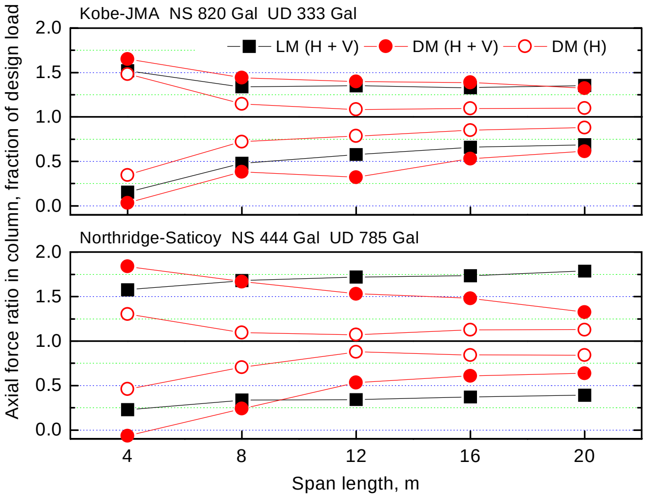
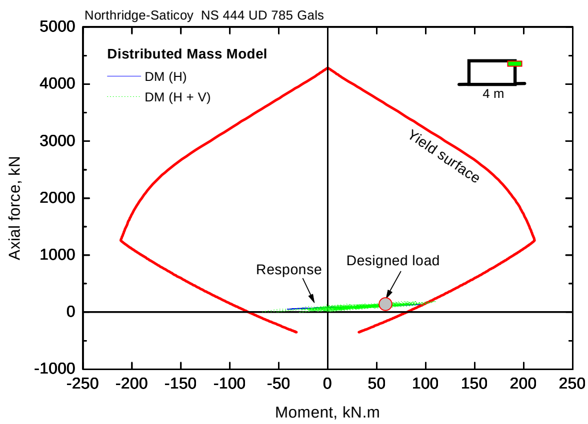


Figure 4: Axial force ratio in columns as a fraction of initial design load



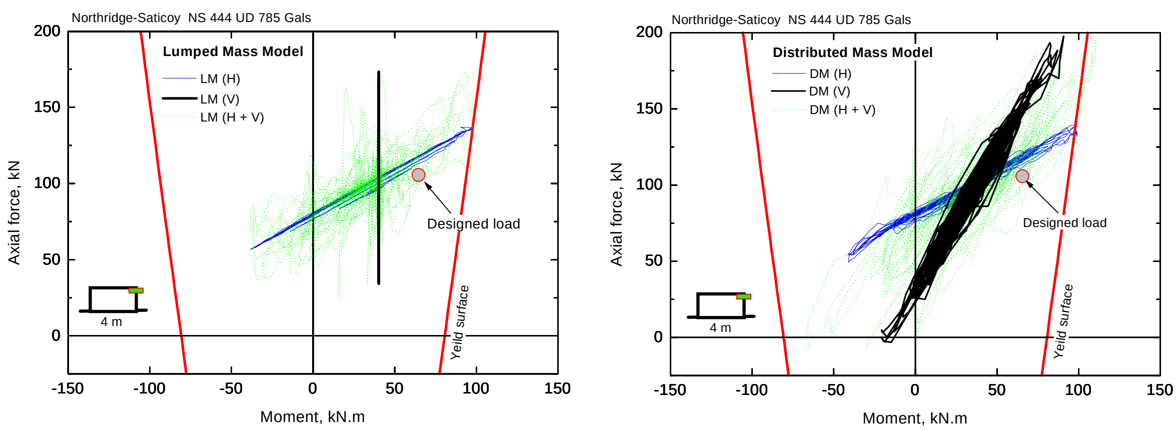


Figure 5: Effect of distributed mass on interaction response diagram at top of column

SIX-STORY TWO-BAY PROTOTYPE FRAME

A six-story two-bay R/C plane frame structure was designed to fulfill the requirements of the "Design Guideline for Earthquake Resistant R/C Buildings Based on Ultimate Strength Concept" introduced by Architectural Institute of Japan in 1990 [AIJ 1990]. The Prototype structure was designed for a seismic coefficient C_b of 0.25. Geometry of sections were determined based on a linear analysis such that inter-story drift angle was less than 1/300 when frame was subjected to inverse triangular equivalent seismic design load. The location of planned yield hinges, weight of structure, dead and live loads at floors, and cross section of columns and girders are shown in Figure 6. Compressive strength of concrete and yielding strength of steel were 30 and 400 MPa; and modulus of elasticity of concrete and steel were 29.2 and 200 GPa, respectively. Member reinforcements are listed in Table 2. A nonlinear pushover analysis under triangular lateral seismic load was carried out to confirm the location of planned hinges (Figure 6).Fundamental natural period of frame was 0.44 and 0.062 seconds for horizontal mode and vertical column mode, respectively.

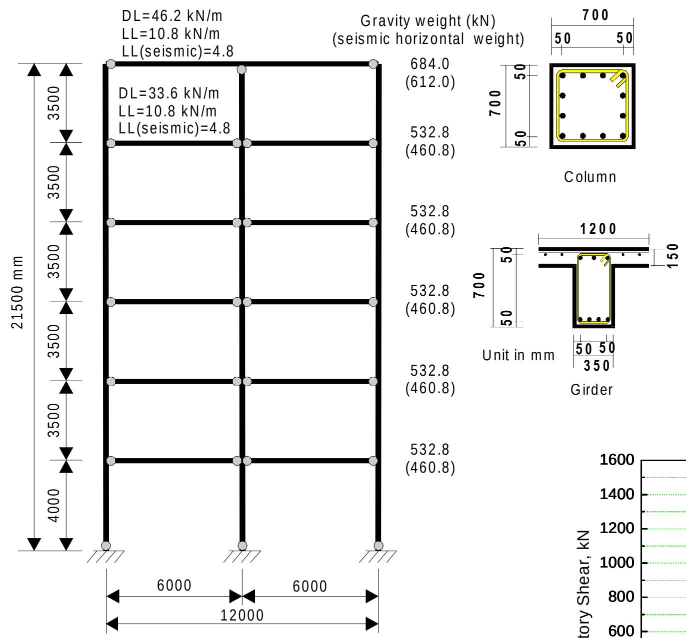


Table 2: Members reinforcements

Story	Member	Bottom steel	Top steel	Slab steel
6 (hinge)	Girder	2D19	2D22	4D13
6 (no hinge)	Girder	4D22	6D22	4D13
5	Girder	2D22	3D22	4D13
4	Girder	3D22	4D22	4D13
3	Girder	4D22	5D22	4D13
2	Girder	4D22	6D22	4D13
1	Girder	5D22	5D25	4D13
Hinge	Column	12D22		
No hinge	Column	12D29		

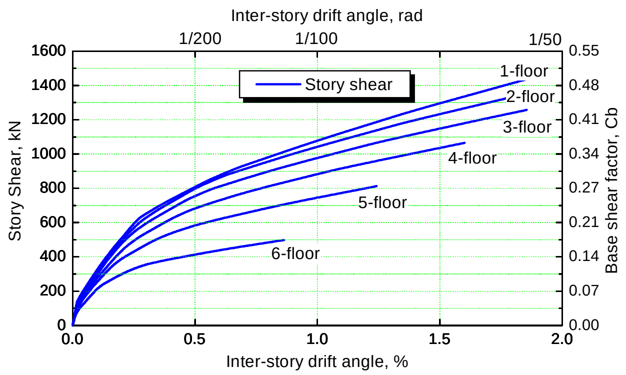


Figure 6: Layout of the prototype structures, location of planed hinges, and results of pushover analysis

The analysis was carried out for different cases of the frame with distributed mass (DM) model under (a) vertical motion alone (V), (b) horizontal motion alone (H), and (c) horizontal and vertical motions (H + V); and (d) the frame with lumped mass (LM) model under vertical and horizontal motions. The frame was subjected to the Kobe-JMA and Northridge-Saticoy records. Figure 7 compares the maximum lateral displacements and story shears. Lateral displacements and story shears are little affected by the distributed mass and vertical motion.

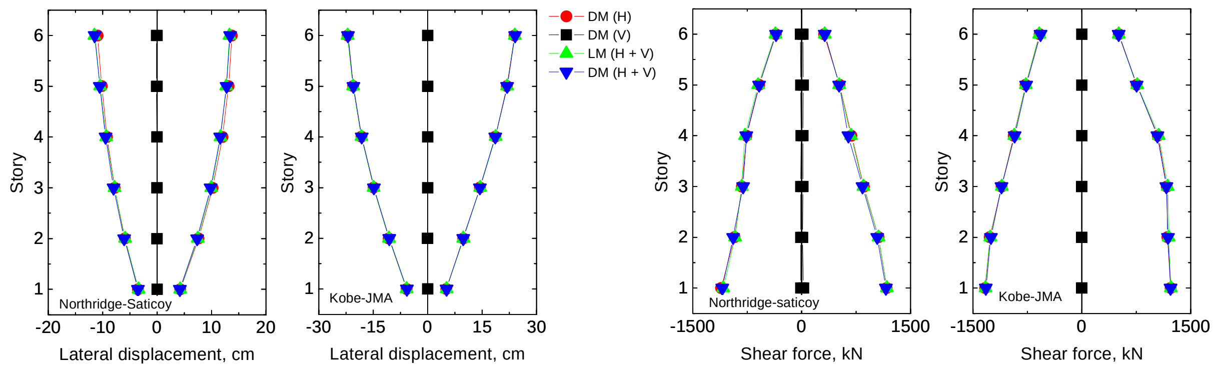


Figure 7: Maximum lateral story displacements and story shears

The maximum vertical displacements at mid-span of frame girders are shown in (Figure 8). The Vertical displacements of girders are considerably affected by distributed mass under vertical motion. The LM model can take into account only the vertical displacements concerning with the columns elongation. The DM model, on the other hand, results to larger vertical displacements by including the vertical vibration of floor systems into the response. It is observed that the vertical displacements are magnified at floor level.

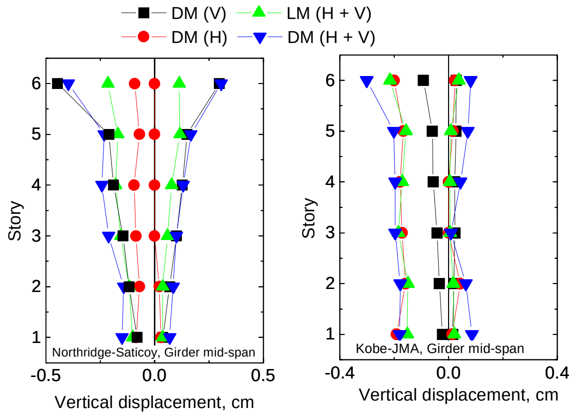


Figure 8: Maximum vertical displacements at the mid-span of frame girders

The maximum vertical displacements at the top of interior and exterior columns are compared in Figure 9. Interior columns are significantly affected by vertical motion while the exterior columns are mainly affected by horizontal motion. Response displacements due to vertical and horizontal motions are comparable in exterior columns of the frame subjected to Northridge record. This is because of extremely strong vertical component of this record. the LM model reasonably estimates the vertical displacement at the interior columns of frame subjected to Kobe record but overestimates the response when frame is subjected to Northridge record. Figure 10 compares the maximum axial forces in the interior and exterior columns. Since the axial forces and the axial displacements in columns were assumed to be linearly proportional, similar trends as to the vertical displacements are observed. The axial forces in columns are significantly influenced by vertical motion, especially at interior columns. Distribution of maximum axial forces is nearly linear over the height of the building. The LM model greatly overestimates the axial force in interior column under Northridge record. The DM model may reduce or enlarge the maximum axial forces in columns when comparing with the results of the LM model. Extremely strong vertical motion of Northridge record results to tension in interior columns, while under Kobe record the interior columns are not experienced tensile forces.

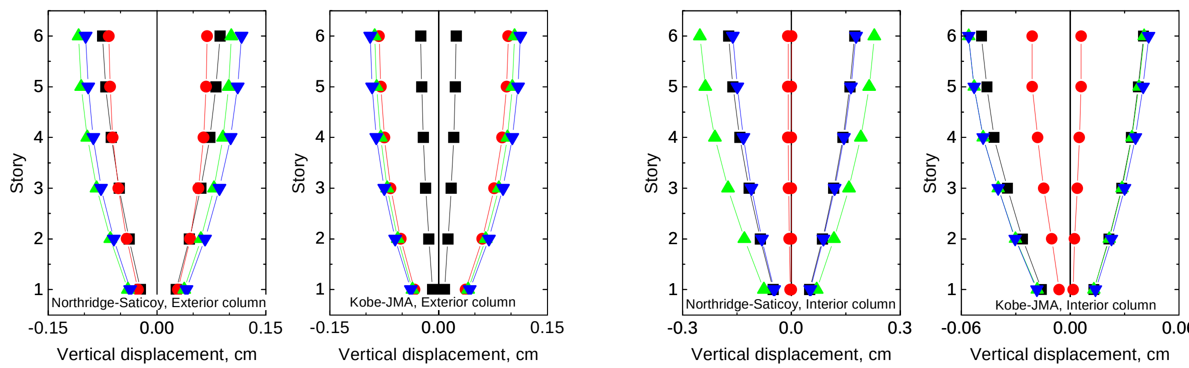


Figure 9: Maximum vertical displacements at the top of interior and exterior columns

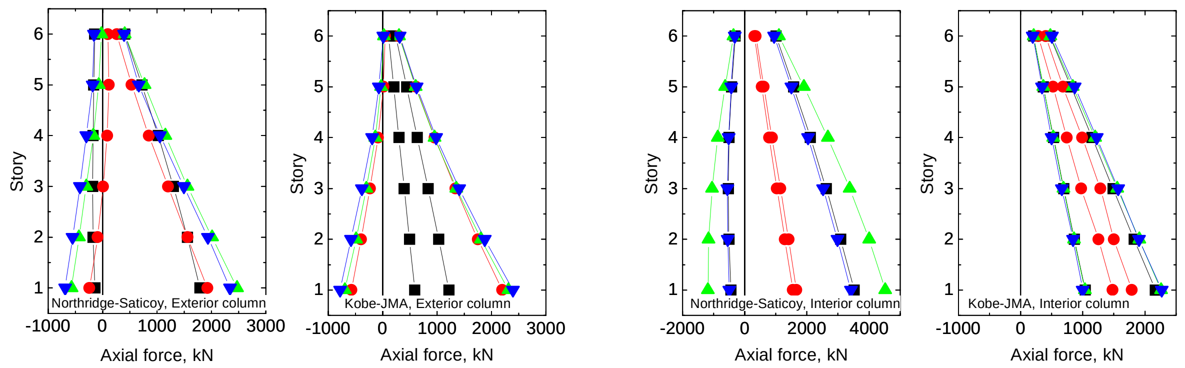


Figure 10: Maximum axial force in the interior and exterior columns

Figure 11 compares the variations of base shear versus the top story lateral drift. It is observed that small discrepancies exist under Northridge record but overall response of the frame is not sensitive to the vertical motion and distributed mass. Lateral story displacements at first story of the frame are presented in Figure 12. The lateral story displacement is very little affected by the vertical motion and the distributed mass.

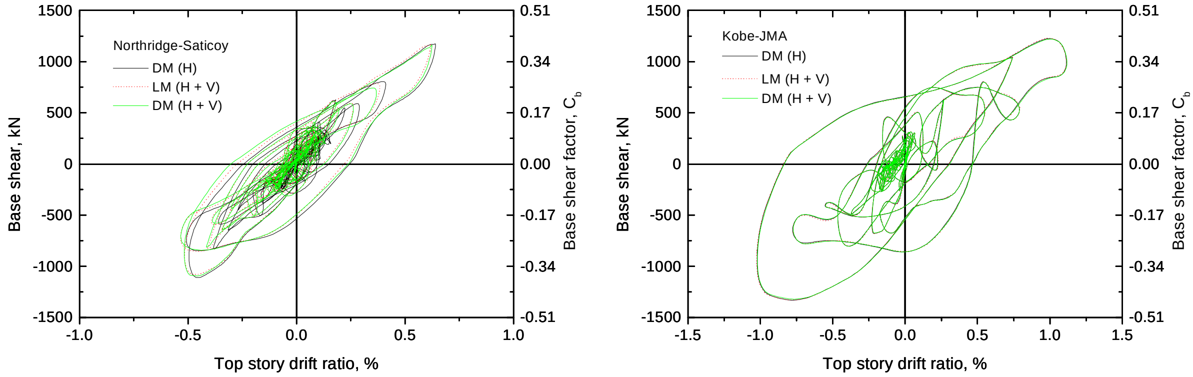


Figure 11: Overall earthquake response of prototype framed structure

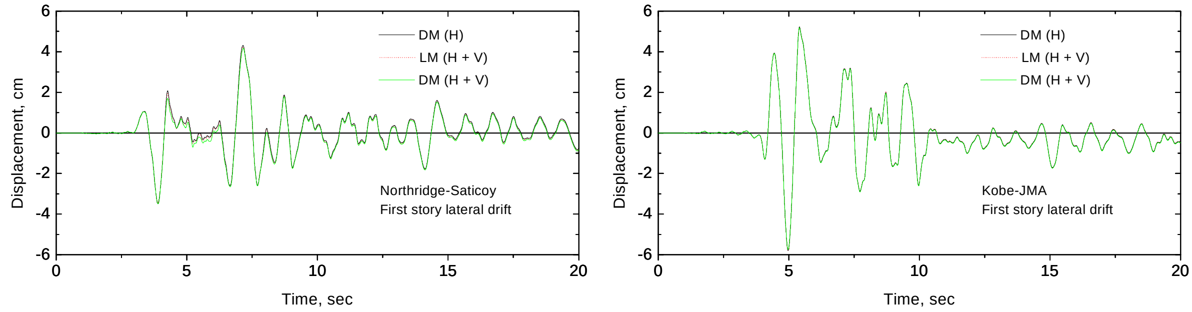


Figure 12: Lateral displacements at first story of the frame

Axial forces in exterior and interior columns at first story of the frame are compared in Figure 13. More fluctuations in column axial forces are observed when the frame is subjected to vertical motion. The sizes of fluctuations are larger under the Northrige record. This is because of stronger vertical ground motion of Northridge record than the Kobe record. Interior columns are much affected by vertical motion than that of exterior columns, which were mainly influenced by the overturning moment due to horizontal motion.

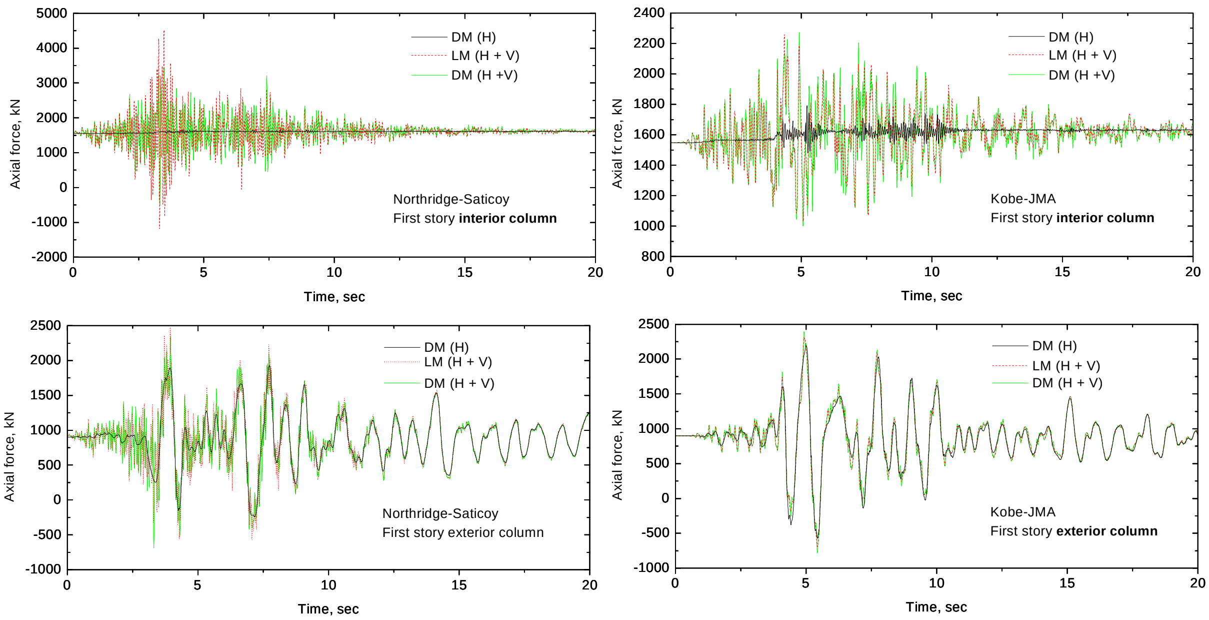


Figure 13: Axial force in exterior and interior columns of first story

Initial gravity load of interior and exterior columns were 1555 and 896-kN, respectively. The design axial load of interior columns were calculated based on gravity load alone. The design lateral seismic load did not influence the axial load of interior columns. Exterior columns were designed for combination of seismic and gravity loads. The design axial load of exterior columns under unilateral seismic load was equal to –259 and +2019-kN. Table 3 listed the maximum fluctuation of axial forces in interior and exterior columns at the first story of the frame under Northridge and Kobe strong motions. The numbers in parenthesis indicate the axial force fluctuation ratio of response to the initial gravity axial load in columns. The value of axial force fluctuation ratio at the interior column under Northridge strong motion is about 120% and 180% for DM and LM models, respectively. The LM model significantly overestimates the axial force of an interior column. Under Kobe earthquake motion, the size of axial force fluctuation ratio in interior column is about 40% for both DM and LM models. Exterior columns are less affected by distributed mass and vertical motion. The contribution of vertical motion to the axial force fluctuation ratio of exterior columns is about 10-20% under Kobe record, and about 40-60% under Northridge record. The ratio is changed about 10% by using LM or DM models.

Figure 14 compares the interaction diagrams of interior and exterior columns. It can be seen that the maximum axial forces can be occurred simultaneously with the maximum bending moment. This is clearly observed in the interior columns under Kobe records. Consequently a column which is designed for the combination effects of lateral seismic load and gravity load may yield by the effect of distributed mass under strong vertical motion.

Table 3: Maximum fluctuation in the axial force of interior and exterior columns

Member	DM (H)		LM (H + V)		DM (H + V)	
	Decrease	Increase	Decrease	Increase	Decrease	Increase
Interior column (Kobe-JMA)	1480 (5 %)	1790 (15 %)	1033 (33 %)	2257 (45 %)	1000 (35 %)	2270 (49 %)
Interior column (Northridge-Saticoy)	1546 (-1 %)	1665 (1 %)	-1182 (176%)	4522 (-190 %)	-491 (125 %)	3414 (120 %)
Exterior column (Kobe-JMA)	-572 (164 %)	2197 (145 %)	-690 (177 %)	2311 (157 %)	-782 (187 %)	2392 (166 %)
Exterior column (Northridge-Saticoy)	-241 (126 %)	1926 (114 %)	-571 (163 %)	2473 (176 %)	-687 (176 %)	2344 (161 %)

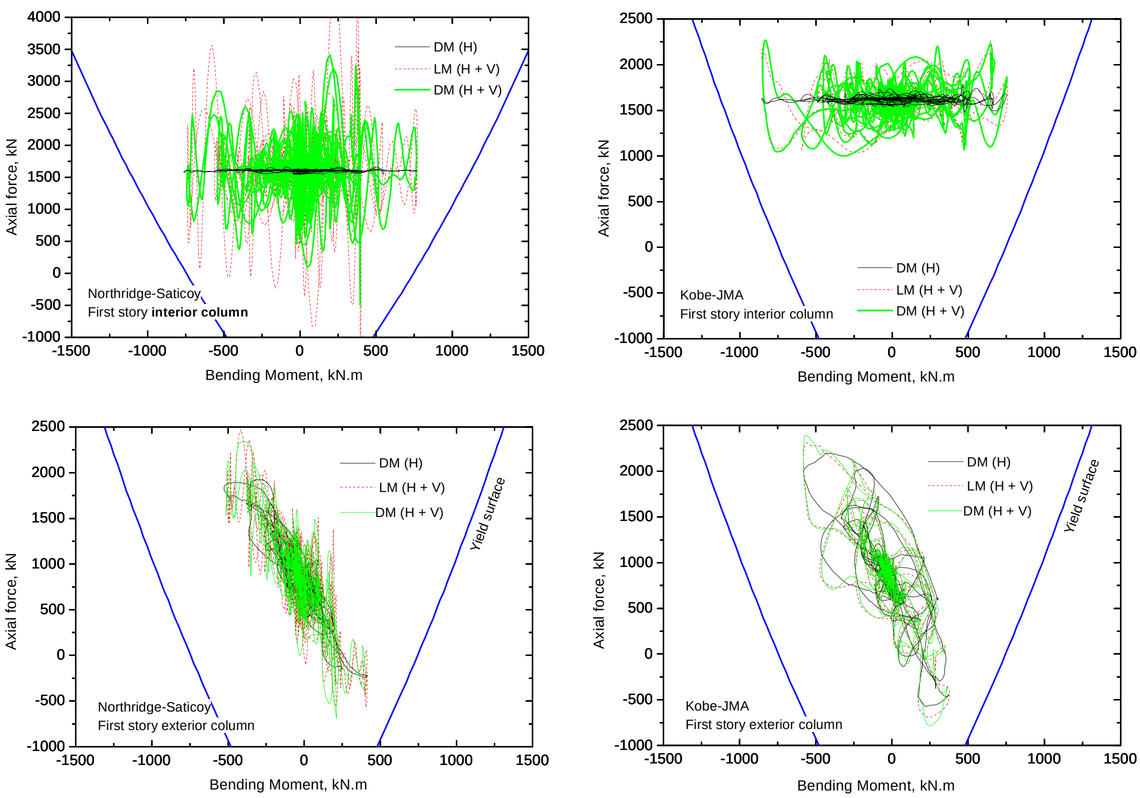


Figure 14: Interaction response diagrams of first story columns

The moment-rotation relationships of the girder-end at the first story of frame are compared in Figure 15. It can be seen that the effects of vertical motion and distributed mass on the moment-rotation relationship are very small. This indicated that the variation in columns axial force due to vertical motion and distributed mass are not affected by the change in shear force in the girders. Therefore the effect of girder shear force was negligible when studying the effect of vertical motion and distributed mass onto axial force of columns.

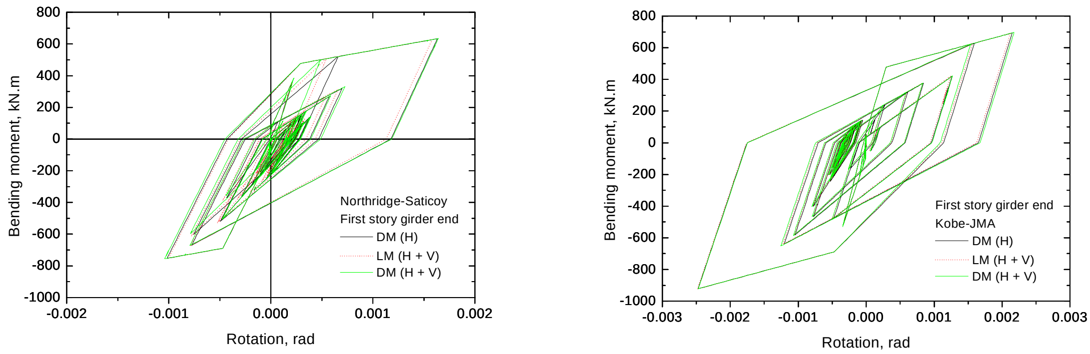


Figure 15: Moment-rotation hysteretic relationship at the exterior end of first story girder

5. CONCLUSIONS

The effect of distributed mass as well as vertical ground motions of two near field earthquakes to the nonlinear dynamic response of five single-story one-bay R/C frames, and a six-story two-bay R/C frame were studied. It was concluded that:

1. The lateral story displacements and story shears were slightly affected by the vertical motion and distributed mass.
2. The vertical component of a ground motion significantly affected the axial forces in columns. This is especially happened when the contribution of lateral seismic load on axial load is small such as in a low-rise building or in the interior columns of an intermediate or a high-rise building.
3. Distributed mass under vertical motion can significantly alter the axial forces in frame columns. Thus lumped mass model must be used carefully when estimating the design load of a non-yielding frame column subjected to vertical motion. Further research is needed to estimate a magnification factor in axial force fluctuation of column due to the effect distributed mass under vertical motion.
4. Vertical vibration caused more fluctuation in column axial forces. The size of fluctuation was proportional to the intensity of vertical ground motion.

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