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RESEARCH ARTICLE

Seismic response of fixed-base and LRB base-isolated RC frame systems under NF and FF excitations

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Abstract

Seismic isolation systems can be used in new structures to reduce the negative effects of the earthquake on the building. The lead rubber bearing (LRB) is one of the most commonly used seismic isolators. This study focused on the behavior of Reinforced Concrete (RC) frame systems with fixed-base and Lead Rubber Bearing systems under Near-Fault (NF) and Far-Fault (FF) records. For this purpose, two-plane frame systems with 4 and 8 story were designed. Nonlinear behavior of both superstructure and isolation system was taken into consideration in modeling. The nonlinear time history analysis method was used in the seismic analysis of reinforced concrete frame systems. Finally, story acceleration, interstory drift ratio, base shear force and distribution of plastic hinges and their damage conditions were evaluated. The results of the analysis showed that the effects of the NF earthquake record on the frame system had generally greater according to the effects of the FF earthquake records.

Keywords

Non-linear analysis; Lead-core rubber bearing; Reinforced concrete; Near-fault; Far-fault

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1. Introduction

Turkey is located in an active seismic zone. Therefore, many earthquakes have occurred until today (Erzincan 1939, Kocaeli 1999, Van 2011, Kütahya 2011). On the other hand, many earthquakes occurred in the world such as Northridge (1994), Kobe (1995), Chi-Chi (1999) and Peru (2019). In consequence of these earthquakes, there were many casualties and financial losses have occurred. A number of methods have been used together with developing technology to minimize such destructive effects of the earthquakes. One of these methods is an LRB isolator. In the case of the proper application of the LRB, it is expected that the performance of the

structure against to earthquakes will increase and also it will exhibit elastic behavior during the earthquake [1].

The first example of rubber isolators was implemented in a primary school in Skopje-Macedonia (1969). In this application, the unreinforced natural rubber isolator was used. Then, seismic isolators have been used in countries such as America, Japan and New Zealand with the developing technologies and knowledge [2]. In Turkey, seismic isolators were used in recent years in buildings required to be utilized after the earthquake such as hospitals and fire stations etc. NF ground motions were defined as ground motions occurring near the earthquake faults.

Malhotra [3] investigated the NF ground motions

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effects on buildings by using the PGA, PGV and PGD parameters of the different earthquake records. It was mentioned in the study, the PGV/PGA ratio was high in the NF motions and also the response characteristics were significantly affected. MacRae et al. [4] idealized the structures as single-degree of freedom systems in their study. They classified the models as short period and medium-long period under the NF effect. It was mentioned that the inelastic demand was high in the structures having medium-long period, whereas structures having short-period do not need high inelastic demand. Moniri [5] investigated the results of illustrious characteristics of NF ground motions on the seismic response of RC structures, by the incremental nonlinear dynamic analysis method. The study showed that near-source outcomes cause most of the seismic energy from the rupture to arrive in a single coherent longperiod pulse of motion and permanent ground displacements. Additionally, in some studies, the effects of NF and FF records on the RC structures were investigated [6-10].

The optimum parameters of LRB isolation system supporting a structure under NF ground motions were investigated [11-12]. The main structures were modeled as a simple linear multidegrees-of-freedom vibration system with lumped masses, excited by NF ground motions. The objective functions selected for optimality of LRB systems were to maximize the seismic energy dissipation [11] or the minimization of both the top floor acceleration and the bearing displacement [12]. These studies showed that there is significant displacement in the LRB under NF ground motions for the low values of the bearing yield strength. The increase in the bearing yield strength can reduce the bearing displacement significantly without much altering to the superstructure accelerations.

The seismic performance of different LRBs with supplemental viscous damping were examined in terms of base and superstructure drift under NF and FF motions [13]. It presented various LRB isolation systems which were systematically compared and discussed for aseismic performances of two actual RC buildings. Parametric analysis of

the buildings fitted with isolation devices was carried out to choose the appropriate design parameters. The efficiency of providing supplemental viscous damping for reducing the isolator displacements was also investigated.

Moreover, to determine the effects of the LRB isolators using different earthquake records, several RC structures were taken into consideration under the NF ground motion. The structures with/without LRB isolator were compared and noticed that the base shear forces were lower, the superstructures have a higher period and the relative interstory displacement decreased, in LRB isolated structures [14]. These results indicate that LRB systems perform well against to earthquake effects [15-19]. In addition, the effects of the NF and FF ground motions were examined comparatively [1, 20]. It is stated the LRB isolators were effective in decreasing the base shear force and relative interstory displacements were reduced by LRB isolator systems.

In this study, the behavior of RC buildings with/without LRB isolator under NF and the FF effects were taken into consideration. For this purpose, two-plane frame systems with 4 and 8 story were designed. The superstructure was modeled using Turkish Earthquake Code (TEC2007) [21]. The substructure systems were modeled by Uniform Building Code (UBC97) [22] because there is no detailed information concerning LRB isolators in the TEC2007 [21]. The analyses were performed by using Ruaumoko software. Finally, story acceleration, interstory drift ratio, base shear force and distribution of plastic hinges and their damage conditions were evaluated.

2. Modeling of building structures

2.1. Design of superstructure

In this study, the single axis of the 4-story and 8-story RC buildings modeled as one bay in the x-direction and three-bay in the y-direction was taken into account. The bay length of the buildings was 7m in both directions and the story height of the buildings were 3m. The considered slab thickness and brick infill wall thickness were 15cm and

13cm, respectively. TEC2007 [21] regulations were taken into account while modeling the buildings. In models the concrete class C25, seismic zone I and local site class Z4 were used. Additionally, the live load, covering load and the brick wall load, selected as 2kN/m², 1.5kN/m² and 2.5kN/m², respectively. Plan and cross-sectional views of the structures were presented in Fig. 1.

The findings based on the structural analyses by the Idestatik software, dimensions of the columns on the corners, columns on the mid-bay and all beams were 40cm×40cm, 50cm×50cm 30cm×50cm for the 4-story building, respectively. On the other hand, for 8-story building, the dimensions of the column on the corners, columns on the mid-bays and all beams were 60cm×60cm, 80cm×80cm and 30cm×50cm, respectively. Furthermore, it was determined by the analysis results that the minimum reinforcement ratio was sufficient for all columns. The amount of reinforcement required for columns and beams were shown in Table 1 and Table 2.

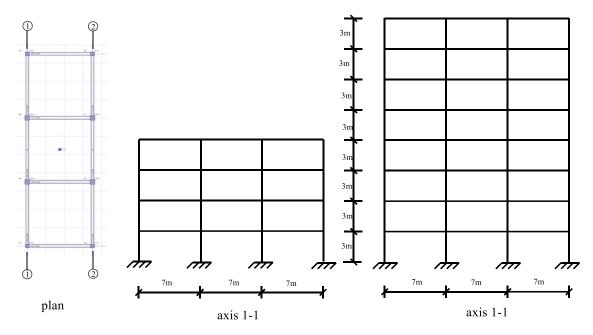


Fig. 1. Plan and cross-sectional view of the 4 and 8 story structures

Table 1. Column and beam steel areas for the 4-story structure

				101 1110 1 1	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,					
A-A		Ste	el Area fo	r Beam (d	cm ²)		Beam		Long. Steel	Column
Axis	Edge	Loc	cation		Loc	cation	Dim.	Column	Area for	Dim.
Story	Region	Top	Bottom	Bays	Top	Bottom	(cm×cm)	Column	Column	(cm×cm)
·		-			-				(cm^2)	
4		7.75	5.09		4.02	5.62		A1, A4	18.47	
		11.56	6.17		4.02	5.62		A2, A3	27.71	
3	A1, A4	10.18	5.15	A1-A2	4.02	5.62		A1, A4	18.47	
	A2, A3	12.25	7.10	A2-A3	4.02	5.62	30×50	A2, A3	27.71	40×40
2		12.60	6.47	A3-A4	4.02	5.62		A1, A4	18.47	50×50
		15.27	7.69		4.02	5.62		A2, A3	27.71	
1		12.60	6.47		4.02	5.62		A1, A4	18.47	
		15.27	7.69		4.02	5.62		A2, A3	27.71	

Table 2.	Column a	nd beam	steel areas	for the 8-s	tory stru	icture				
A-A		Stee	el Area Fo	or Beam (c	cm ²)		Beam		Long. Steel	Column
Axis	Edge	Loc	cation		Loc	cation	Dim.	Column	Area For	Dim.
Story	Region	Top	Bottom	Bays	Top	Bottom		Column	Column (cm ²)	(cm×cm)
8		8.48	4.62		3.08	5.08		A1, A4	36.19	
0		10.49	5.34		3.08	6.03		A2, A3	64.34	
7		12.25	6.16		3.08	4.62		A1, A4	36.19	
/		11.72	6.16		3.08	6.03		A2, A3	64.34	
6		13.19	7.09		4.02	4.62		A1, A4	36.19	
U		13.73	7.09		4.02	6.03		A2, A3	64.34	
5		15.74	8.17	A1-A2	4.02	4.62		A1, A4	36.19	
3	A1, A4	18.22	9.11	A1-A2 A2-A3	4.02	6.03	30×50	A2, A3	64.34	60×60
4	A2, A3	18.88	10.71	A2-A3 A3-A4	4.62	4.62	30^30	A1, A4	36.19	80×80
4		18.35	10.71	A3-A4	4.62	6.03		A2, A3	64.34	
3		19.35	10.71		5.09	4.62		A1, A4	36.19	
3		19.28	11.66		4.62	6.03		A2, A3	64.34	
2		19.35	10.71		5.09	4.62		A1, A4	36.19	
Z		19.28	11.66		4.62	6.03		A2, A3	64.34	
1		16.35	8.69		4.02	5.62		A1, A4	36.19	

4.02

6.03

Table 2. Column and beam steel areas for the 8-story structure

2.2. Design of isolation system

The existing regulations in TEC2007 [21] no provisions regarding the seismic isolation of structures; therefore, in modeling the isolation system, the determination of design criteria and seismic analyses were based on the UBC97 [22].

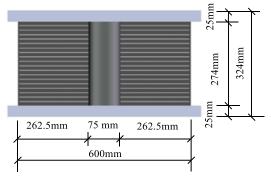
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The selected parameters are as follows:

18.12

- Seismic zone factor: zone 4, Z = 0.40
- Site soil profile category: SD
- Seismic source type: A type (M = 7), slip rate
 SR = 5 mm/year
- Establishment of the near-source factors: Δ >10 km, $N_a = 1$ $N_v = 1.2$
- Seismic coefficient: $C_v = 0.768$, $C_a = 0.44$
- Effective damping of the isolation system: Lead plug laminated rubber, $\beta_{eff} = 0.15$
- Damping reduction factor: B = 1.35

Two different LRB isolators were designed for inner and outer columns in 4 and 8-story frame systems (Fig. 2). The shear modules of the used rubber in the modeling were taken as G_A =0.5MPa, G_B =1MPa and γ =1.5 for large strains, beside of this G_A =0.7MPa, G_B =1.4MPa and γ =0.20 were taken for small strains. Additionally, the Bulk Modulus of the rubber was 2000MPa and the yielding strength of the lead was 10.5MPa. The mechanical



64.34

A2, A3

Fig. 2. A typical cross section of a lead rubber bearing

properties of the designed isolators were given in Table 3.

3. Applied ground motions

The FF and NF earthquake records used in this study were selected from the PEER NGA database. In the dynamic analysis of fixed-base and LRB base-isolated structures, 10 ground motion records have been used, including 5 FFs and 5 NFs. The Joyner—Boore distances of selected NF earthquake records are less than 4km. This distance is in the range of 28-36 km in the FF earthquake records. Other characteristics of the mentioned earthquake records were given in Table 4. In the analyses, the earthquake records were scaled as 0.35g.

Table 3. The properties of isolators for outer and inner columns in frame syste
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Incloton Duomenties	Outer 1	Bearing	Inner Bearing		
Isolator Properties	4-story	8-story	4-story	8-story	
Bearing Height (mm)	324	324	324	324	
Characteristic strength (kN)	44.55	83.89	89.11	167.78	
Yield strength (kN)	49.48	93.1	98.96	186.2	
Effective stiffness (kN/m)	650	1150	1300	2300	
Post-yield stiffness (kN/m)	470	840	940	1680	
Vertical stiffness (kN/m)	788814	1195590	1194373	2740220	
Bearing diameter(mm)	600	800	600	800	
Lead core diameter (mm)	75	105	105	145	

Table 4. The characteristics of NF and FF ground motion data used in time history analysis

Earthquake	$M_{\rm w}$	Ground Motion	Recording Station	Comp.	R _{JB} (km)	PGA (g)	V _{s30} (m/sn)	Tp (s)
Northridge (1994)	6.7	NF	Jensen Filter Plant Adm. Build.	22	0	0.41	373.07	3.157
Kobe (1995)	6.9	NF	Takatori	90	1.46	0.671	256	1.554
Chi-Chi (1999)	7.6	NF	TCU049	N	3.76	0.244	487.27	10.22
Kocaeli (1999)	7.51	NF	Yarimca	150	1.38	0.3218	297	4.949
Duzce (1999)	7.14	NF	Duzce	270	0	0.515	281.86	-
Northridge (1994)	6.7	FF	Lake Hughes #1	0	35.46	0.086	425.34	-
Kobe (1995)	6.9	FF	Sakai	90	28.08	0.1267	256	-
Chi-Chi (1999)	7.6	FF	CHY036	E	30.81	0.094	233.14	-
Kocaeli (1999)	7.51	FF	Goynuk	90	31.74	0.1199	347.62	-
Duzce (1999)	7.14	FF	Mudurnu	90	34.3	0.0591	535.24	-

4. The results of time history analysis

4.1. Displacement responses

In consequence of using NF records, the maximum story displacement values of fixed-base and LRB base-isolated frame systems were given in Figs. 3 and 4. Maximum story displacements in fixed-base 4-story frame system was obtained from Chi-Chi earthquake and minimum story displacements from Kocaeli earthquake. The difference in roof displacements for these two earthquakes was more than 45%. For LRB base-isolated 4-story frame system, the maximum story displacements were calculated from Kocaeli earthquake and the minimum story displacements from earthquake. Furthermore, in 8-story frame systems with fixed-base and LRB base-isolated, minimum story displacements were obtained from Duzce earthquake. The maximum story displacements were obtained from Northridge and Chi-Chi

earthquakes in fixed-base and LRB base-isolated cases, respectively. Additionally, in the LRB baseisolated 4-story frame system, the design displacement values were exceeded by Kocaeli, Chi-Chi and Northridge earthquake records. The design displacement values were exceeded in Chi-Chi and Northridge earthquake records for the LRB base-isolated 8-story frame system.

Under the effects of the FF records, the obtained minimum and maximum story displacement values for fixed-base and LRB base-isolated frame systems were given in Figs. 5 and 6. The obtained minimum and maximum displacement values were in the Kocaeli and the Northridge earthquakes for 4-story fixed-base frame system, respectively. The difference in roof displacements for these two earthquakes was more than 45%. Additionally, the obtained minimum and maximum story displacement values were in the Kocaeli and the Duzce earthquakes for 4-story LRB base-isolated frame system, respectively.

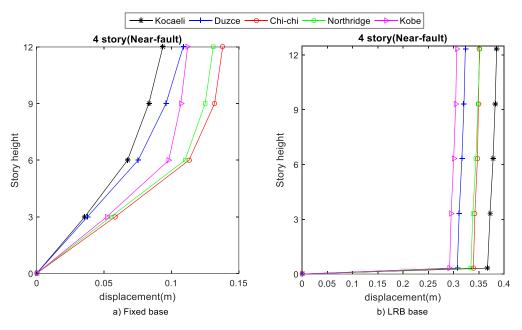


Fig. 3. Variation of displacements with structure height for the 4-story structure under NF records

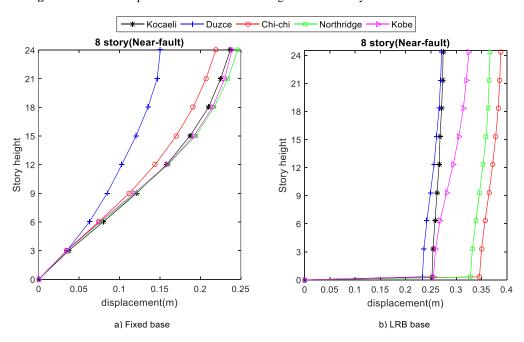


Fig. 4. Variation of displacements with structure height for the 8-story structure under NF records

Furthermore, in the 8-story fixed-base frame system, while the acquired minimum story displacement value was in the Kocaeli earthquake, the maximum one was in the Chi-Chi earthquake record. The difference in roof displacements for these two earthquakes was more than 65%. The minimum and maximum story displacement values

were obtained from the Northridge and the Duzce earthquakes for 8-story LRB base-isolated frame system, respectively. Also, the design displacement values in 4 and 8-story LRB base-isolated frame systems for FF earthquake records have not been exceeded.

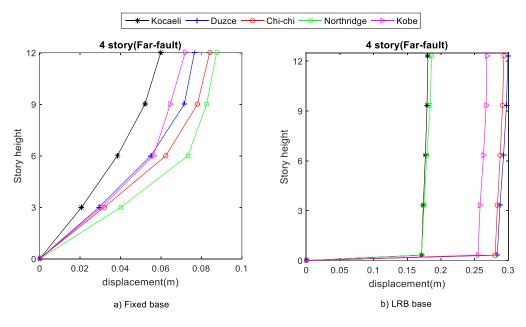


Fig. 5. Variation of displacements with structure height for the 4-story structure under FF records

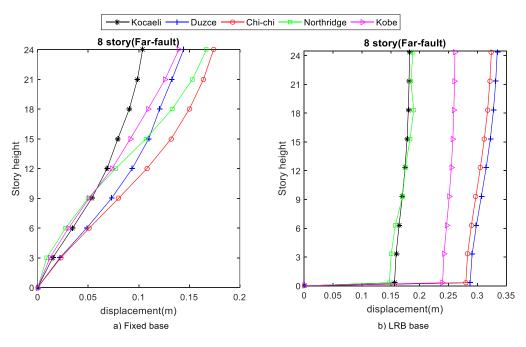


Fig. 6. Variation of displacements with structure height for the 8-story structure under FF records

4.2. Absolute story acceleration

The story acceleration values of 4 and 8-story fixed-base and LRB base-isolated RC frames under the effects of NF and FF records were presented in Table 5 and 6. It can be seen from the tables the acceleration values of two fixed-base frames were less at the base level than at the top stories under both records. On the other hand, the story acceleration values of both LRB base-isolated frame systems were not observable change unlike the fixed-base frame systems.

Table 5. Acceleration values of base-isolated and fixed-base for the 4-story structure under NF reco

	Absolute max. story acceleration (m/sn ²)									
Story	Koc	aeli	Du	zce	Chi-	-Chi	North	ridge	Ko	be
	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB
4	5.99	4.07	6.46	3.94	6.90	4.03	6.41	4.18	6.12	3.85
3	5.19	4.10	4.95	3.94	6.02	4.08	5.90	4.09	5.40	3.68
2	4.96	3.95	4.22	3.99	5.61	4.11	5.44	4.05	5.12	3.60
1	3.58	3.81	3.75	4.06	4.71	4.09	4.01	4.11	3.80	3.54
Isolation	-	3.78	-	4.05	-	4.01	-	4.09	-	3.56
Ground motion	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43

Table 6. Acceleration values of base-isolated and fixed-base for the 8-story structure under NF records

				Absolute max. story acceleration (m/sn ²)						
Story	Koc	aeli	Du	zce	Chi-	-Chi	North	ridge	Ko	be
	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB
8	6.62	4.08	6.37	4.17	6.50	4.32	7.61	4.12	6.30	4.08
7	5.43	4.09	5.39	4.09	5.33	4.21	5.64	4.08	5.86	3.95
6	5.76	4.11	4.30	4.01	4.75	4.11	5.22	4.01	5.44	3.60
5	4.97	4.14	4.57	3.94	4.87	4.11	4.78	3.95	5.05	3.56
4	4.31	4.10	4.65	3.89	5.84	4.02	5.60	4.08	5.83	3.51
3	3.90	3.93	4.80	3.90	5.75	3.94	5.30	4.02	5.28	3.63
2	3.60	3.72	3.60	3.94	4.22	3.89	4.35	3.96	4.25	3.75
1	3.46	3.55	3.40	3.92	3.72	3.87	3.62	3.97	3.71	3.80
Isolation	-	3.47	-	3.96	-	3.86	-	3.91	-	3.79
Ground motion	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43

Comparing the story accelerations, there was a significant decrease at the LRB base-isolated system according to the fixed-base system. For Kocaeli, Duzce, Chi-Chi, Kobe and Northridge Earthquake records the top story acceleration values of the LRB base-isolated system were 32.05%, 39%, 41.59%, 34.79% and 37.09% smaller than the fixed-base 4-story frame system, respectively. Additionally, for 8-story frame system, the LRB base-isolated system had 38.37%, 34.54%, 33.54%, 45.86% and 35.24% smaller acceleration values than the fixed-base structure, respectively.

The story acceleration values of the 4 and 8-story frame systems under FF records were presented in Tables 7 and 8. The acceleration

values of the LRB base-isolated frame systems seems to be significantly reduced compared with fixed-base systems. When compared top story accelerations in the 4-story systems for Kocaeli, Duzce, Chi-Chi, Kobe and Northridge earthquake records, they were decreased by 40.31%, 45.94%, 34.61%, 40.19%, and 38.36% in LRB base-isolated case frame system, respectively. Additionally, when this comparison was made for the 8-story frame system with same respect, the top story acceleration of the LRB base-isolated structure decreased by 41.94%,48.75%, 28.40%, 37.09%, and 35.21% according to fixed-base system.

When the values given in the Tables 5-8 compare, it can be seen the story acceleration values for NF records are greater than FF ones.

Table 7. Acceleration values of base-isolated and fixed-base for the 4-story structure under FF record	Table 7.	Acceleration	values of ba	ase-isolated an	nd fixed-base f	for the 4-story	structure under FF records
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			A	Absolute r	nax. story	accelerat	ion (m/sn ²	2)		
Story	Koc	aeli	Du	zce	Chi-	-Chi	North	ridge	Ko	be
	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB
4	5.78	3.45	6.16	3.33	5.98	3.91	6.27	3.75	5.84	3.60
3	6.33	3.49	6.10	3.30	5.11	3.91	5.17	3.70	4.62	3.60
2	5.30	3.70	4.14	3.27	4.15	3.79	4.49	3.55	4.21	3.55
1	3.57	3.98	3.49	3.45	3.58	3.68	3.67	3.43	3.52	3.50
Isolation		4.05		3.65	-	3.58	-	3.29	-	3.51
Ground motion	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43

Table 8. Acceleration values of base-isolated and fixed-base for the 8-story structure under FF records

			A	Absolute max. story acceleration (m/sn ²)							
Story	Kocaeli		Duzce		Chi-Chi		Northridge		Ko	be	
	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB	Fixed	LRB	
8	6.08	3.53	6.38	3.27	5.95	4.26	6.12	3.85	6.22	4.03	
7	5.85	3.46	5.47	3.33	4.46	4.21	5.55	3.82	5.25	3.99	
6	5.38	3.39	4.59	3.51	4.79	4.11	5.20	3.79	5.29	3.90	
5	5.97	3.42	5.22	3.55	5.23	4.06	5.12	3.60	4.78	3.51	
4	6.80	3.58	6.11	3.41	4.63	3.94	4.45	3.40	3.40	3.30	
3	5.74	3.90	6.19	3.51	4.66	3.78	4.33	3.30	3.36	3.26	
2	4.36	4.14	4.99	3.47	4.26	3.73	4.11	3.37	3.61	3.51	
1	3.53	4.24	3.58	3.44	3.65	3.71	3.60	3.54	3.65	3.64	
Isolation		4.24		3.44	-	3.70	-	3.55	-	3.65	
Ground motion	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	

4.3. Base shear force

Variation of base shear forces with time under NF excitations for the LRB base-isolated and fixedbase 4-story structures were given in Fig. 7. According to the graphs for fixed-base systems, the maximum shear force value obtained in the Kocaeli earthquake as 804.6kN and the minimum one was in the Duzce earthquake as 780.4kN. Additionally, for LRB base-isolated structure, the maximum shear force value obtained in the Kocaeli earthquake as 387.6 kN and the minimum one was in the Kobe earthquake as 340kN.

Moreover, variation of base shear forces with time under NF excitations for the LRB base isolated and fixed-base 8-story structures were given in Fig. 8. According to the graphs for fixed-base systems, the maximum shear force value obtained in the Kobe Earthquake as 1500kN and the minimum one was in the Duzce earthquake as 1320kN. Additionally, for LRB base-isolated structure, the maximum shear force value obtained in the Kocaeli earthquake as 818.4kN and the minimum one was in the Chi-Chi earthquake as 732kN.

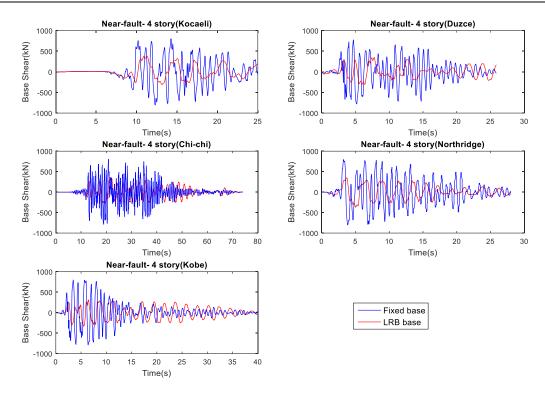


Fig. 7. Variation of base shear force with time for the LRB base-isolated and fixed-base 4-story structure

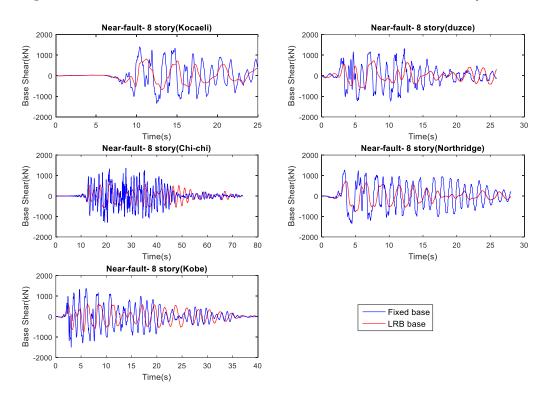


Fig. 8. Variation of base shear force with time for the LRB base-isolated and fixed-base 8-story structure

On the other hand, the graphs showing the variation of the base shear force with time of the 4story RC structure with fixed-base and LRB baseisolated systems for the FF records were given in Fig. 9. The maximum base shear force value obtained by the Northridge earthquake record as 802kN and the minimum one was in the Duzce earthquake as 775kN for fixed-base system. Additionally, for LRB base-isolated structure the maximum shear force value in the Chi-Chi earthquake as 366kN, the minimum one was in the Northridge earthquake with 300kN.

The variation of the base shear force with time of the 8-story RC building with fixed-base and LRB base-isolated system for the FF records were given in Fig. 10. The maximum base shear force value in the Duzce earthquake as 1490kN and the minimum one was in the Northridge earthquake as 1250kN. Additionally, for LRB base-isolated structure the maximum shear force value in the Chi-Chi earthquake as 744kN, the minimum one was in the Kocaeli earthquake with 586kN.

4.4. Interstory drift ratio

The maximum interstory drift ratios, obtained by NF and FF records for 4 and 8-story buildings, were given in Table 9. The maximum interstory drift ratio occurred at the 1st story in the fixed-base 4story building analyzed by the NF records. The maximum interstory drift ratios for Kocaeli, Duzce, Chi-Chi, Kobe and Northridge earthquakes were 1.06%, 1.27%, 1.27%, 1.73% and 1.84%, respectively. This ratio, for all NF records at the LRB base-isolated 4-story building, was obtained on the 2nd story and the values were calculated as lower than 0.22%.

The maximum interstory drift ratio in the 8story fixed-base building was calculated on the 1st and 2nd story for the Chi-Chi and Duzce earthquakes, respectively. This value, it was obtained on the 3rd story for the remaining earthquake records. Additionally, the maximum interstory drift ratios for the Kocaeli, Duzce, Chi-Chi, Kobe and Northridge earthquakes were 1.42%, 1.18%, 1.31%, 1.44% and 1.45%, respectively. On the other hand, the maximum interstory drift ratio in the LRB base-isolated 8-story frame system was calculated on the 4th story of the frame system for the Northridge earthquake and on the 3rd story for other earthquakes. The maximum interstory drift ratios in this frame system were less than 0.5% for all earthquakes.

The maximum interstory drift ratios were obtained in the range of 0.78% - 1.34% and at the 1st story level for all FF earthquake records applied to 4-story fixed-base frame system. These ratios for 4-story LRB base-isolated frame system were calculated on 2nd story level and less than 0.22%. For the 8-story fixed-base structure the maximum interstory drift ratios for all FF earthquake records were calculated in the range of 0.78% - 1.02%. Additionally, the maximum drift ratio was calculated at the 3rd story level in Kobe, Chi-Chi and Kocaeli earthquakes, and at the 2nd and 4th story levels in Duzce and Northridge earthquakes. On the other hand, for 8-story LRB base-isolated system the maximum drift ratios were computed less than 0.50%. The maximum drift ratio was calculated at the 4th story level in Kobe, Chi-Chi and Northridge earthquakes, and at the 3rd story levels in Kocaeli and Duzce earthquakes, for this frame system.

When the maximum interstory drift ratios obtained were examined, it can be said that interstory drift ratios for fixed-base 4 and 8-story frames at the NF records were generally greater than those at the FF. These ratios obtained from the LRB base-isolated frame system for all NF and FF earthquake records significantly decreased with respect to the fixed-base frame system ones. Additionally, the interstory drift ratios obtained from the 8-story LRB base-isolated frame system were greater than the values obtained from the 4story LRB base-isolated system for all NF and FF earthquake records.

4.5. Plastic hinge distribution

The damage in RC elements will be quantified with the Park and Ang damage index [23]. This index combines the maximum lateral displacement effects with the plastic dissipated energy at one end of the element according to the following expression:

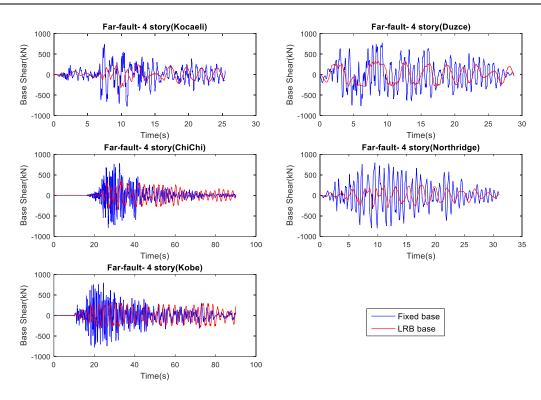


Fig. 9. Variation of base shear force with time for the LRB base-isolated and fixed-base 4-story structure

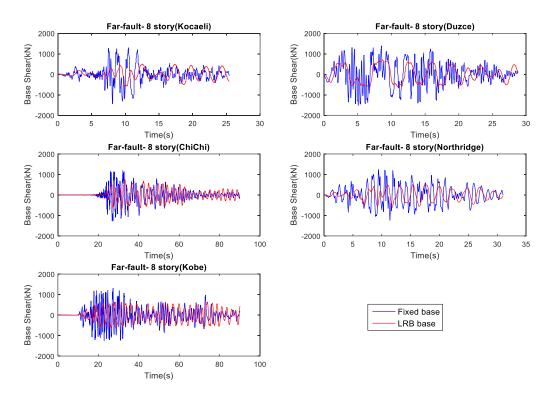


Fig. 10. Variation of base shear force with time for the LRB base-isolated and fixed-base 8-story structure

		Maximum interstory drift									
Earth	quake Record	4 st	ory	8 story							
	-	Fixed-base	LRB base	Fixed-base	LRB base						
	Kocaeli	1.06	0.21	1.42	0.37						
	Duzce	1.27	0.20	1.18	0.33						
NF	Chi-Chi	1.27	0.19	1.31	0.38						
	Kobe	1.73	0.17	1.44	0.48						
	Northridge	1.84	0.18	1.45	0.36						
	Kocaeli	0.78	0.19	0.78	0.23						
	Duzce	0.98	0.18	0.88	0.31						
FF	Chi-Chi	1.10	0.21	1.02	0.47						
	Kobe	1.02	0.17	0.98	0.38						
	Northridge	1 34	0.17	0.99	0.30						

Table 9. Maximum interstory drift ratios of base-isolated and fixed-base condition for the 4 and 8 story structure

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{Q_V \delta_u} \int dE \tag{1}$$

where γ_m is the maximum lateral displacement, γ_u is the ultimate displacement, β is a model constant parameter, $\int dE$ is the hysteretic energy absorbed by the element during the earthquake, Q is the yield strength of the element. According to this damage index, D < 0.1: no damage; $0.1 \le D < 0.25$: minor damage; $0.25 \le D < 0.40$: moderate damage $0.40 \le$ D < 1: severe damage; and $D \ge 1$: collapse.

The weighted damage index and maximum member damage index values obtained from NF and FF earthquake records were given in Tables 10 and 11. When the weighted damage index values for NF earthquake records were examined, it can be said that the maximum damage was occurred on the 4-story fixed base frame system by the Northridge earthquake. Also, the maximum weighted damage index was obtained from the Kobe earthquake for the 8-story fixed-base frame system. With considering the maximum member damage index values, a moderate damage was formed in some members of the 4 and 8-story fixed-base frame systems under NF earthquake records except the Kocaeli and the Duzce earthquakes, respectively.

The weighted damage index values of fixed base 4and 8-story frame systems were in the range of 0.066-0.087 for FF conditions. According to the maximum member damage index values, the minor damages were occurred in some members of the 4story fixed-base frame system at all earthquakes except the Duzce earthquake. In addition, the minor member damages were observed in some members of the 8-story fixed base frame systems which were analyzed by using all FF earthquake records.

For both NF and FF earthquake records, there was no plastic hinge formation in the 4-story LRB base-isolated frame system. Also, since the damage index values were less than 0.1 for the 8-story LRB base-isolated frame system, it can be said that there is no damage in the frame system. The distributions of the plastic hinge of the 4 and 8-story building with fixed-base and LRB isolated conditions can be seen in Figs. 11 and 12 for the NF record of the Chi-Chi earthquake.

5. Results

In this study, the analysis of the 4 and 8-story RC frame systems for fixed-base and LRB baseisolated, was carried out using NF and FF records. The results of the analyses are as follows.

Table 10	Damage	history	of the 4	1-8 story fram	e systems for	NF records

Support case	Fixed-base				LRB base			
NF earthquake Records	Max. member damage index		Weighted damage index		Max. member damage index		Weighted damage index	
	4 -story	8-story	4 -story	8-story	4 -story	8-story	4 -story	8-story
Kocaeli	0.248	0.311	0.081	0.111	-	0.086	-	0.042
Duzce	0.27	0.241	0.085	0.090	-	0.074	-	0.036
Chi-Chi	0.36	0.30	0.101	0.108	-	0.092	-	0.047
Northridge	0.347	0.322	0.119	0.121	-	0.09	-	0.045
Kobe	0.35	0.325	0.101	0.126	-	0.096	-	0.045

Table 11. Damage history of the 4-8 story frame systems for FF records

Support case	Fixed-base				LRB base			
FF earthquake Records	Maximum member damage index		Weighted damage index		Maximum member damage index		Weighted damage index	
	4 -story	8-story	4 -story	8-story	4 -story	8-story	4 -story	8-story
Kocaeli	0.152	0.167	0.066	0.076	-	0.050	-	0.029
Duzce	0.209	0.207	0.078	0.085	-	0.077	-	0.040
Chi-Chi	0.23	0.24	0.077	0.087	-	0.078	-	0.039
Northridge	0.313	0.218	0.086	0.085	-	0.070	-	0.037
Kobe	0.23	0.206	0.074	0.084	-	0.086	-	0.044

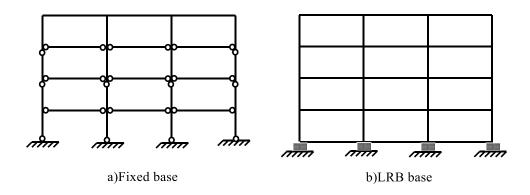


Fig. 11. Plastic hinge locations for the 4-story structure

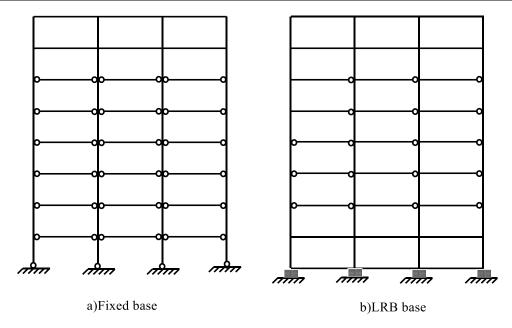


Fig. 12. Plastic hinge locations for the 8-story structure

- In this study, the analysis of the 4 and 8-story RC frame systems for fixed-base and LRB baseisolated, was carried out using NF and FF records. The results of the analyses are as follows.
- For all the earthquake records, the values of the base shear forces, maximum interstory drift ratio and absolute story acceleration for LRB base-isolated system were decreased reference to the fixed-base frame system.
- In the fixed-base frame systems, the plastic hinges occurred in both beams and columns. For 4-story LRB base-isolated frame system, there was no plastic hinge but, for 8-story system the formation of plastic hinges was observed in some of beams.
- In reference to the Park and Ang damage index, in the fixed-base frame systems, the moderate damage occurred in some members. On the other hand, for LRB base-isolated frame systems, there was no damage. Also, damages caused by NF earthquake records in frame systems are generally greater than damages caused by FF earthquake records.
- In frame systems, interstory drift ratios, story displacements and base shear forces obtained by using NF earthquake recordings were higher

mostly than the values obtained by using FF earthquake records.

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