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Comparing the dynamic behavior of a hospital-type structure with fixed and isolated base

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Abstract. The level of ductility is determined by depending on the intended use of the building, the region's seismic characteristics and the type of structural system when buildings are planned by engineers. Major portion of seismic energy is intended to be consumed in the plastic zone in structural systems of high ductility, so the occurrence of damages in load bearing and non-load bearing structural elements is accepted in planning stage under severe earthquakes. However, these damages must be limited among specific values in order not to endanger buildings in terms of the bearing capacity. Isolators placed between the basement and upper structure make buildings behave elastically by reducing the effects of seismic loads and improving seismic performance of building significantly. Thus, damages can be limited among desired values. In this study, the effectiveness of seismic isolation is investigated on both fixed based and seismic isolated models of a hospital building with high ductility level with regard to lateral displacements, internal forces, structural periods and cost of the building. Layered rubber bearings are interposed between the base of the structure and foundation. Earthquake analysis of the building are performed using earthquake records in time domain (Kocaeli, Loma Prieta and Landers). Results obtained from three-dimensional finite element models are presented by graphs and tables in detail. That seismic isolation reduces significantly the destructive effects of earthquakes on structures is seen from the results obtained by seismic analysis.

Keywords: seismic isolation; isolators; dynamic analysis in the time domain

1. Introduction

Many earthquakes have occurred and caused death of a lot of people and loss of properties all over the world for years. Different studies have been conducted on dynamic analyses and earthquake engineering to minimize these losses. One of the developments in engineering area is earthquake isolators protecting structures against destructive effects of earthquakes by reducing forces transferred to the structure.

Load carrying capacity, stiffness, ductility, stability and inelastic deformation of a building can be increased with the changes made on the load-bearing system. Seismic isolation systems

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developed as an alternative to traditional methods are implemented to minimize destructive effects of earthquakes on structures by increasing energy dissipation capacity and lengthening the period (Zayas *et al*. 1990), (Constantinou *et al*. 1990).

The main purpose of seismic isolation is to reduce seismic loads transferred to structures by lengthening structural period rather than improving the strength of structures against seismic loads. Seismic isolation systems have been successfully applied on new and existing structures. More than % 50 of the peak responses can be reduced by properly adjusting the properties of base isolators Yang and Lam (2015).

Rubber bearings were used for the first time in an elementary school building located in the city of Skopje for seismic isolation for structures Jangid and Data (1995). This building is a three-story reinforced concrete structure was built in 1969. Natural rubber blocks were used as support system. Steel plates were not placed in rubber, so desired rigidity could not be obtained in the vertical direction. However, vertical loads of the building are transferred to foundation in safe thanks to the high vertical rigidity of isolators.

The most comprehensive literature researchers about base isolator and base isolation systems are carried out Bukle and Mayes (1990), Jangid and Data (1995), Kunde and Jangid (2003), Morgan and Mahin (2008), Khoshnoudian and Rabiei (2010). Yurdakul and Ates (2011) studied on a two dimensional and eight-story building using isolated and fixed based models of it to investigate effectiveness of the seismic isolation system on the buildings. Bagheri and Khoshnoudian (2014) investigated the effect of impact on seismic response of isolated structures mounted on double concave friction pendulum bearings subjected to near field ground motions.

Seismic isolation has become a technology with the production of high-quality investment units, the presence of full scale test facilities and the development of non-linear analysis methods, so advanced academic studies have been conducted on this system used in many structures in the world and its applications have been included in the specifications Erdik (2007).

Ataturk Airport Terminal Building, Bolu Viaduct, Antalya International Airport, Gulburnu Bridge, Istanbul Cevahir Mall, Erzurum State Hospital and Kocaeli State Hospital etc. in Turkey and Foothill Communities Law Building, Justice Center Building, San Francisco Hall, LA City Hall, Oakland City Hall, San Francisco International Airport, Benicia-Martinez Bridge, Rio Hondo Bridge, Seattle, Washington Stadium, The New Zealand Parliament House, West Japan Postal Computer Center, San Diego Coronado Bay Bridge, Utah State Capital, The Old Bank Shopping Arcade, Tan Tzu Medical Center, The University of Southern California Teaching Hospital, Xindian General Hospital in Taiwan, The USC Hospital, GTB Hospital in India, The Arrowhead Medical Center in Southern California, Okinawa Naval Hospital, Yuzawa Hospital and Takasu Hospital in Japan and San Bernardino Hospital in California etc. in the world can be given as sample structures applied seismic isolation systems.

The aim of this study is to investigate effectiveness of seismic isolation system in terms of dynamic behavior on a hospital-type structure of high ductility level subjected to earthquake ground motions. For this purpose, a nine-story hospital-type building was modeled by ideCAD (2013) structural packaged software. Time domain linear dynamic analyses are carried out on fixed based and isolated models of the hospital building. The results of the dynamic characteristics, displacements and internal forces of both models are compared with each other to reveal the effectiveness of the base isolation system on dynamic behavior of building.

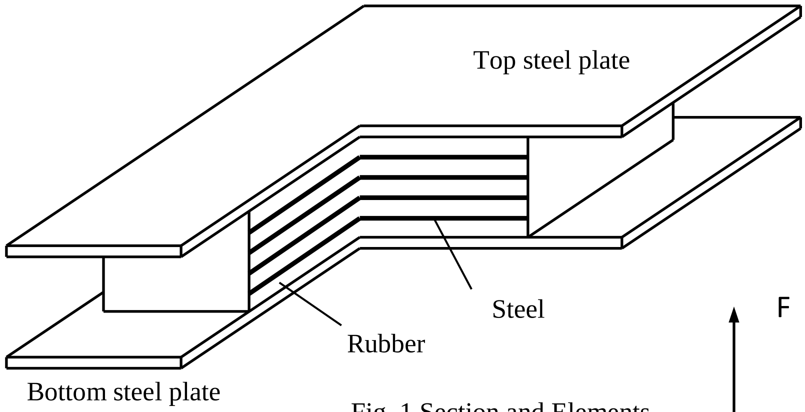

Fig. 1 Section and Elements

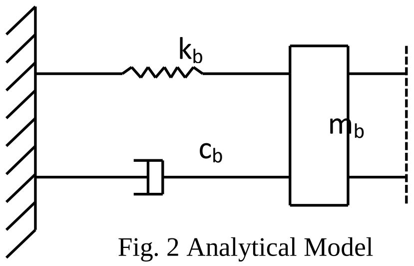

Fig. 2 Analytical Model

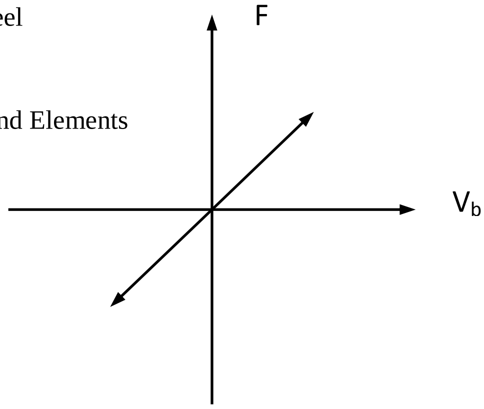

Fig. 3 Force-Displacement Relation

2. Layered rubber bearing system

Layered rubber bearing (LRB) is used widely in isolation systems. The basic elements of this system are being used in layers of steel and rubber plates. Also, parallel effects of damping and stiffness are the most important features of this system. LRB system has high damping capacity with horizontal flexibility and vertical rigidity. This bearing system is defined by the natural frequency and damping coefficient. Also, the damping constant is dependent on the deformation of the support. This result was obtained from experimental studies conducted by Tracis (1984). In his study, Tracis indicated that the damping ratio is dependent on the deformation of the support. Section, elements, analytical model and force-displacement relation of the LRB is given in Figs. 1, 2, 3.

2.1 The mechanical properties of the rubber bearings

The mechanical properties of layered rubber bearings have been studied for a long time. That behavior of this type of bearings is compatible with nonlinear theory is specified by literature. However, realistic analyses including non-linear techniques are very difficult. Simple analysis methods based on the theory of linear were used and these results were confirmed by experiments. Finite element method is a method commonly used and based on the linear theory.

The most important mechanical property of rubber bearings is rigidity in the horizontal direction. This lateral stiffness is calculated as below

$$K_H = \frac{G_A}{t_r} \quad (1)$$

Here; *G* is the shear area of rubber, *A* is the full cross sectional area of rubber bearing and t_r is the total thickness of rubber. The maximum amount of deformation of the bearing rubber is

$$\gamma = \frac{D}{t_r} \quad (2)$$

Where; *D* denotes the maximum horizontal displacements of the rubber bearing. In addition, vertical and bending rigidity is again explained by the linear elastic theory. These two parameters are used in the design of rubber bearing. Vertical stiffness of the rubber bearing and vertical frequency of seismic isolated structure are proportional to each other. Vertical stiffness of rubber bearing should be calculated under self-weight loads to be able to determine vertical frequency of seismic isolated structure. The first behavior of a rubber bearing under vertical loads is a non-linear behavior and depends on several factors. Normally, the behavior of rubber shows many differences before the vertical deformation is not completed in full. However, it is not possible to express these conditions in analyses, but this uncertainty depending on the steel plates placed in bearing and labors in construction is not effective in the behavior of the bearing. Vertical stiffness of the rubber bearing is calculated as below

$$K_v = \frac{E_c A}{t_r} \quad (3)$$

Where; *A* is the cross sectional area of rubber bearing, t_r is the total thickness of rubber and E_c is the pressure module of composite material formed by rubber and steel under a specific vertical load and its value is determined by the shape factor of a single rubber sheet. Shape factor

$$S = \frac{\text{Loaded Area}}{\text{Side Surface Area}} \quad (4)$$

Accordingly; for a circular bearing

$$E_c = 6GS^2 \quad (5)$$

And for a square rubber bearings

$$E_c = 6,73GS^2 \quad (6)$$

Plastic deformation occurring at the edges of the bearing is

$$\gamma_c = GS\frac{\Delta}{t_r} \quad (7)$$

Where; Δ denotes the vertical displacement of the rubber bearing and is used in the design of bearing. The average deformation of the bearing is as follow

$$\gamma_{ave} = \sqrt{6}S\frac{\Delta}{t_r} \quad (8)$$

GZY-800 type of rubber bearing isolator which is one of the different types of isolators included by ideCAD (2013) structural software is used in this study. Rubber bearing isolators and their some characteristics are given in Table 1.

Table 1 The characteristics of rubber isolators included in ideCAD structural software

Name	Diameter	Height (m)	V. Pressure Capacity (KN)	V. Stiff. (KN/m)	H. Stiff. (KN/m)	Damp. Ratio (%)	Design Disp. (mm)	Max. Disp. (mm)
GZP-300	0,32	0,1105	1019,716	540449,593	530,252	5	64	160
GZY-300	0,32	0,1105	1019,716	815772,97	856,562	22	64	160
GZP-400	0,42	0,124	1835,489	764787,16	866,759	5	80	200
GZY-400	0,42	0,124	1835,489	1019716,213	1447,997	18	80	200
GZP-500	0,51	0,158	2549,291	1019716,213	1070,702	5	98	245
GZY-500	0,51	0,158	2549,291	1427602,698	1784,503	18	98	245
GZP-600	0,62	0,197	4078,865	1723320,40	917,745	5	112	350
GZY-600	0,62	0,197	4077,865	2243375,669	1957,855	29	112	350
GZP-700	0,72	0,237	5608,439	2528896,208	1152,279	5	133	385
GZY-700	0,72	0,237	5608,439	3110134,45	1937,461	25	133	385
GZP-800	0,82	0,300	7341,957	3569006,745	2447,319	6	200	440
GZY-800	**0,82**	**0,300**	**7341,957**	**4440864,108**	**5506,468**	**32**	**200**	**440**
GZP-900	0,92	0,346	9177,446	4308301,00	3161,12	6	200	495
GZY-900	0,92	0,346	9177,446	5098581,065	3161,12	32	200	495
GZP-1000	1,02	0,376	11216,878	5832776,738	5832776,738	6	200	550
GZY-1000	1,02	0,376	11216,878	6867788,694	6867788,694	32	200	550

Table 2 Material properties of building elements

Concrete Grade	C30/37
Modulus of Elasticity (kN/m^2)	32000000
Poisson's Ratio	0,2
Weight Per Unit of Volume (kN/m^3)	25
Modulus of Subgrade Reaction (kN/m^3)	50000

Table 3 Cross-section properties of building elements

Element	Shape	b(m)	h(m)	Area(m^2)
Beam	Rectangular	0,30	0,60	0,180
Column	Rectangular	0,40	0,80	0,320
Shear wall	Rectangular	0,25	3,60	0,900
Shear wall	Rectangular	0,25	1,80	0,450
Shear wall	Rectangular	0,25	2,00	0,500

3. Analytical study

In this study, a nine-story hospital-type building is used as an example to investigate the effectiveness of seismic isolation on both fixed based and seismic isolated models of building with high ductility level with regard to lateral displacements, internal forces, structural periods and cost of the building. The building is modeled as spatial by ideCAD structural software. Cross sections of vertical bearing elements are constants along with building height and story heights of the building are three meters. The building is located in the first-degree seismic zone, building importance coefficient (I) is one and a half and Local site class is Z2 according to Turkish Seismic Code 2007. Material and cross-section properties of building elements are given in Table 2 and Table 3.

Story plan, three-dimensional analytical model, three-dimensional finite element model and mode shapes of building can be shown respectively in Figs. 4-7.

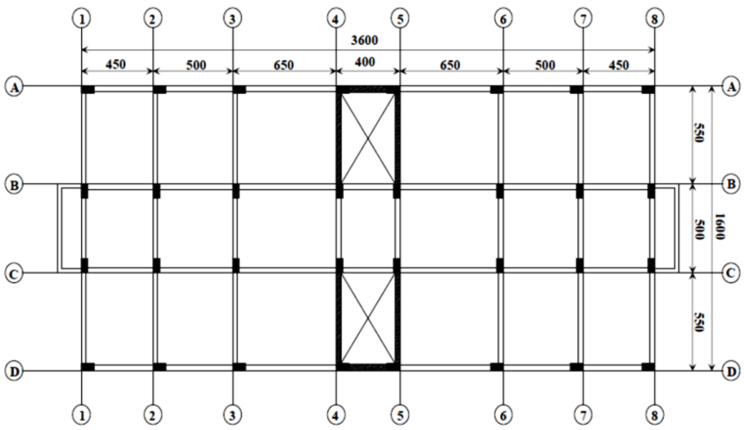

Fig. 4 Story plan of the building

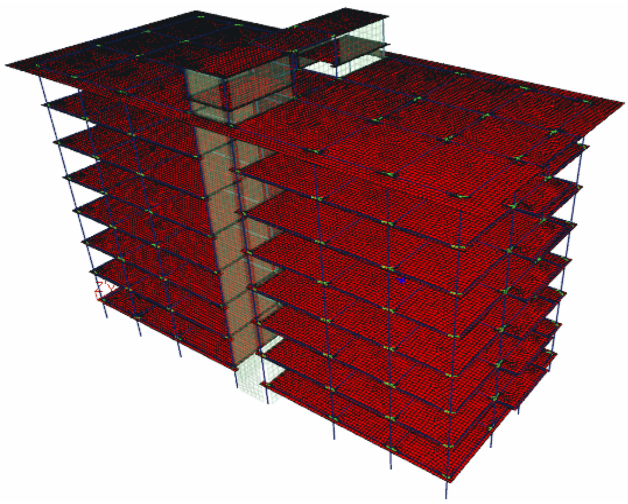
Fig. 5 Three-dimensional analytical model of the building

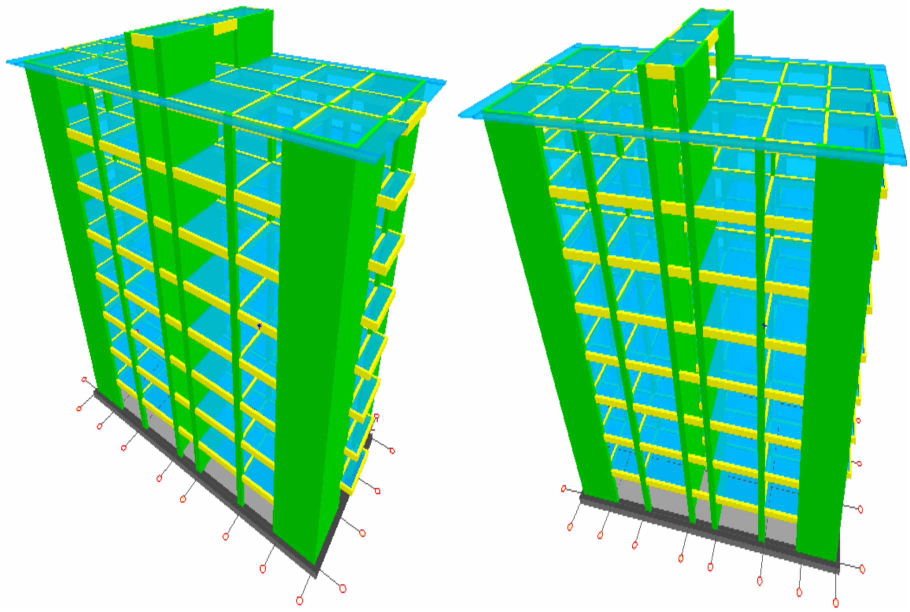

Fig. 6 Three-dimensional finite element model of the building

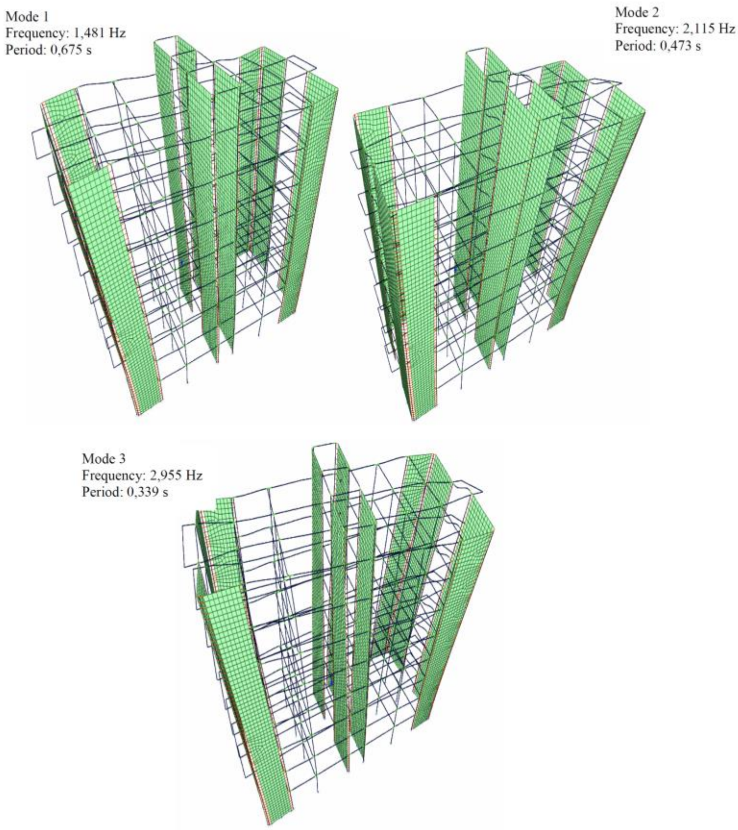

Fig. 7 Periods, frequencies and mode shapes of the building

Table 4 Period and frequency values of fixed and isolated models of structure

Modes	**Fixed Model**		**Isolated Model**	
	Periods (s)	**Frequencies (Hz)**	**Periods (s)**	**Frequencies (Hz)**
1	0,620	1,613	0,675	1,481
2	0,436	2,291	0,473	2,115
3	0,311	3,220	0,339	2,955
4	0,152	6,574	0,163	6,137
5	0,102	9,806	0,109	9,141

Table 5 Earthquake records for time history analyses of structure

Record ID	**Earthquake Name**	**Date (D/M/Y)**	**Recording Station**	**Record**	**M_W**	**r (km)**	**Site Condition**
P1100	Kocaeli	17/08/1999	Goynuk	GYN090	7,4	35,5	B
P0740	Loma Prieta	18/10/1989	Fremont - Mission San Jose	FRE000	6.9	43	B
P0818	Landers	28/06/1992	North Palm Springs	NPS090	7.3	24,2	D

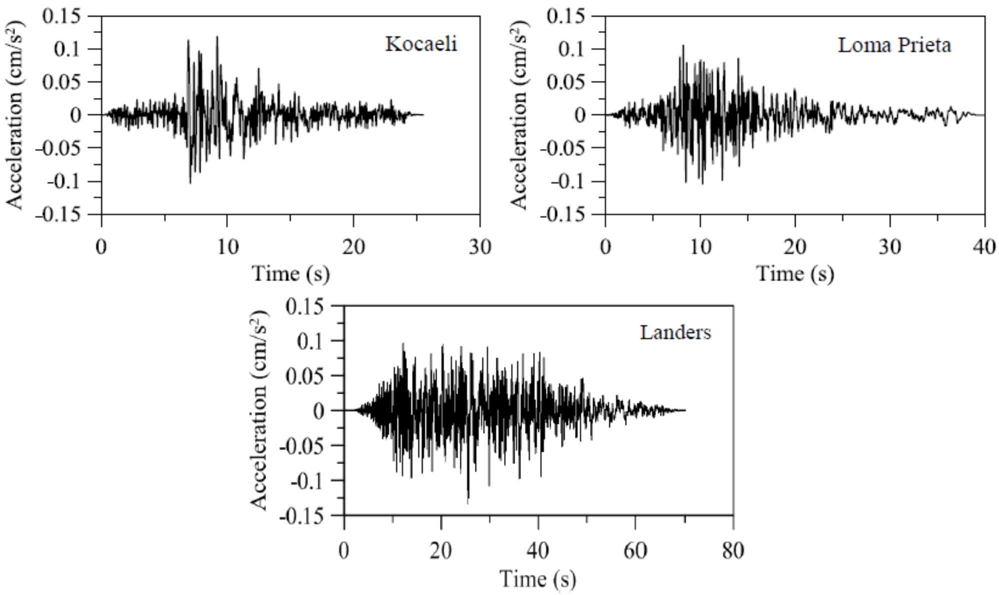

Fig. 8 Acceleration records of earthquakes

The most important task of the earthquake engineering is to protect structures against earthquake forces, so different seismic analysis methods have been used to determine structural responses and make design of structures under earthquake forces. Generally, equivalent lateral force method and spectral modal analysis are preferred to be able to obtain the effects of earthquake forces on structural responses. However, time history analyses have been used commonly in earthquake engineering area to determine earthquake performances of structures in recent years. Advances in computer technology and structural analysis have led to common usage of this seismic analysis type. One of the most important advantages of time history analysis than the other seismic analyses is that real earthquake records are used for seismic analysis of structures Ergun and Ates (2014). In this study, Earthquake analysis of fixed based and isolated models of the building are performed using time domain dynamic analyses. Earthquake records used for linear time history analyses are given in Table 5 with some their characteristics.

Earthquake acceleration records used for linear time history analyses of building are shown in Fig. 8.

4. Numerical results

The effects of seismic isolation system on the hospital building in terms of lateral displacements, internal forces, structural periods and cost of the building are examined by the help of ideCAD structural software. Earthquake records are applied along both *x* and *y* axes of the building. Floor displacements and relative floor displacements of each story along both *x* and *y* axes of the building are taken into account as structural response after linear time history analyses.

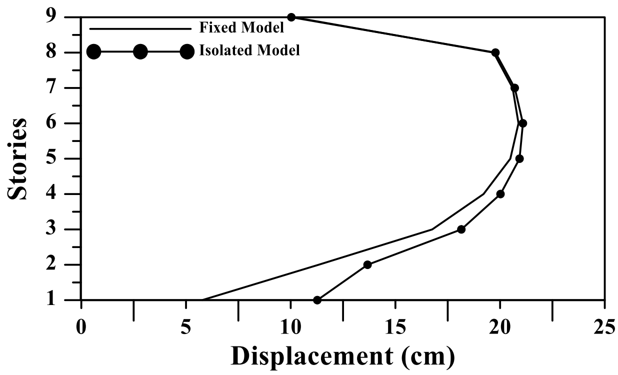

Fig. 9 Variations of relative displacements along *x* axis and the height of the building under the effects of earthquake records

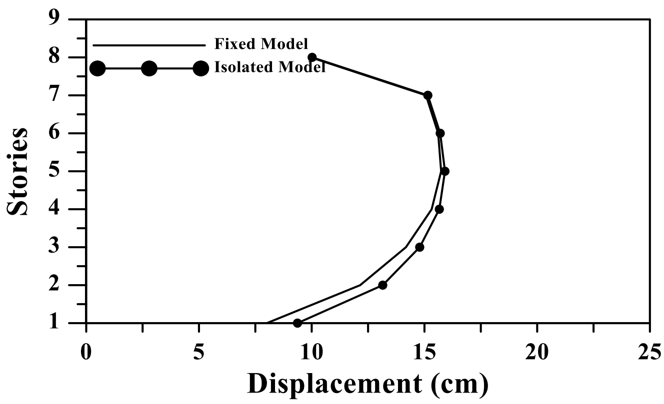

Fig. 10 Variations of relative displacements along *y* axis and the height of the building under the effects of earthquake records

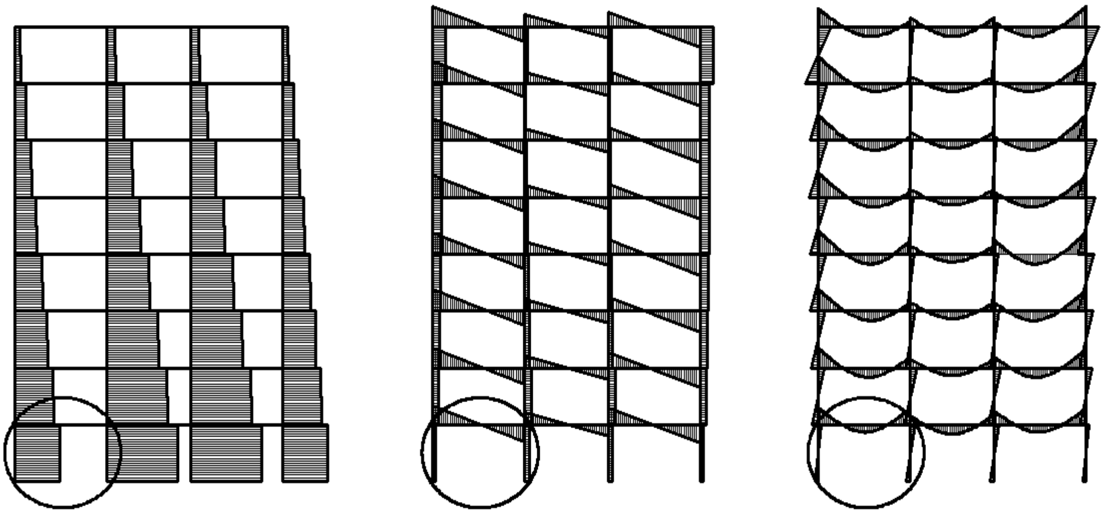

Fig. 11 Axial, shear and bending moment diagrams of fixed model under Kocaeli Earthquake

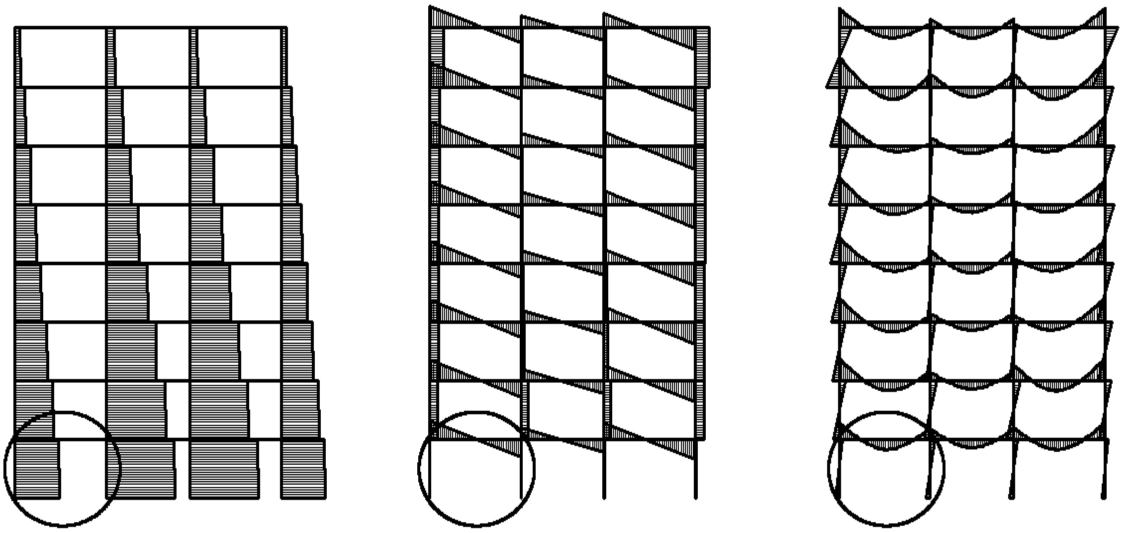

Fig. 12 Axial, shear and bending moment diagrams of isolated model under Kocaeli Earthquake

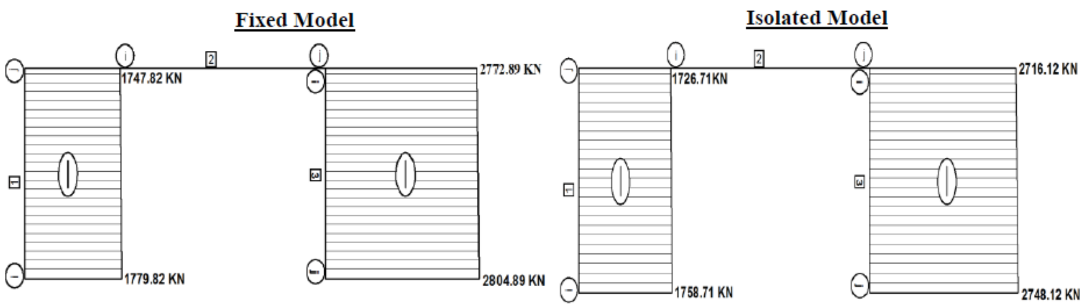

Fig. 13 Axial forces of encircled frames under Kocaeli earthquake

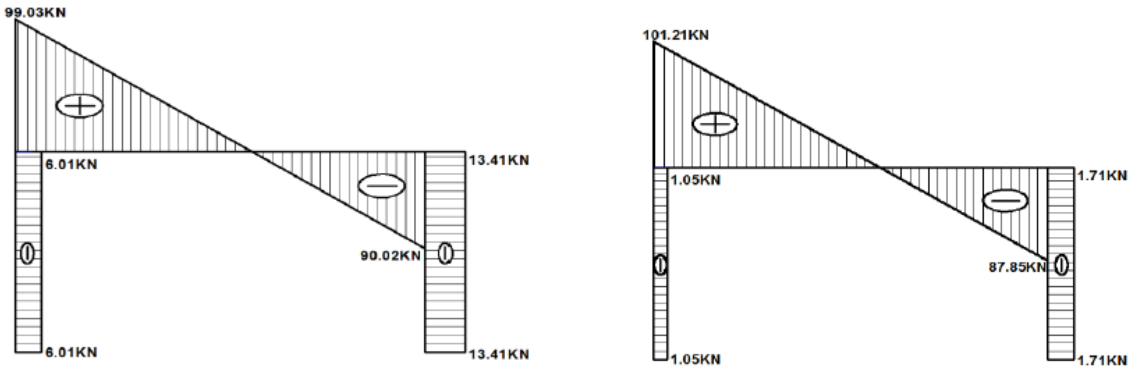

Fig. 14 Shear forces of encircled frames under Kocaeli earthquake

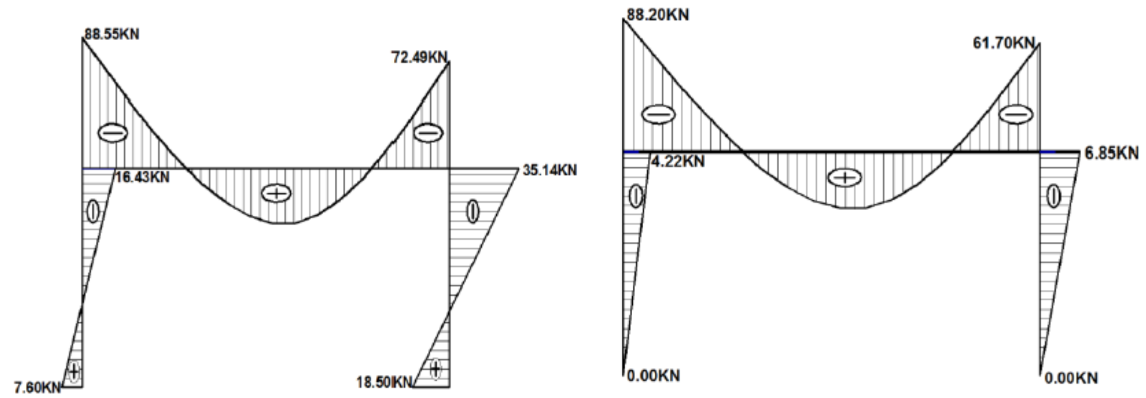

Fig. 15 Bending moments of encircled frames under Kocaeli Earthquake

Table 6 Internal forces of considered frame system under vertical loads and Kocaeli Earthquake

Element No	Internal Forces	G+Q+Ex				G+Q+Ey			
		Fixed Based Model		Isolated Based Model		Fixed Based Model		Isolated Based Model	
		i	j	i	j	i	j	i	j
Element-1	N	1793,15	1756,12	1773,16	1741,16	1779,82	1747,82	1758,71	1726,71
	V	9,33	-9,33	1,37	-1,37	6,01	-6,01	1,05	-1,05
	M	16,03	-21,31	0,00	5,49	7,60	-16,43	0,00	4,22
Element-2	N	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	V	98,40	-89,43	100,64	-87,32	99,03	-90,00	101,21	-87,85
	M	-86,97	-71,00	-86,71	-59,75	-88,55	-72,49	-88,20	-61,07
Element-3	N	2773,40	2805,40	2717,05	2749,05	2772,89	2804,89	2716,12	2748,11
	V	-12,99	12,99	-1,65	1,65	-13,41	13,41	-1,71	1,71
	M	-33,68	15,49	-6,61	0,00	-35,14	18,50	-6,85	0,00

Maximum Relative floor displacements of the building under earthquake records are given in Figs. 9-10.

Internal forces of both models of building attained from time history analyses are compared with each other and the results are presented by the help of tables and figures. The maximum values of axial force, shear force and bending moment for 3-3 axis are obtained from G+Q+EYKocaeli combination shown in Figs. 11-12.

Maximum internal forces of encircled frames above are given in Figs. 13, 14, 15.

The values of normal force, shear force and bending moment are obtained from Kocaeli, Loma Prieta and Landers earthquakes for elements 1-2-3 are given as below in tables.

Also, Economical analysis of fixed and isolated model of the structure has been done and values are given in Table 9.

Table 7 Internal forces of considered frame system under vertical loads and Loma Prieta Earthquake

Element No	Internal Forces	G+Q+Ex				G+Q+Ey			
		Fixed Based Model		Isolated Based Model		Fixed Based Model		Isolated Based Model	
		i	j	i	j	i	j	i	j
Element-1	N	1816,65	1784,65	1800,37	1768,37	1783,15	1751,15	1761,80	1729,80
	V	9,40	-9,40	1,36	-1,36	6,02	-6,02	1,06	-1,06
	M	16,10	-21,50	0,00	5,43	7,61	-16,46	0,00	4,23
Element-2	N	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	V	98,41	-89,50	100,65	-87,44	99,22	-90,50	101,38	-88,32
	M	-86,99	-71,22	-86,72	-60,14	-89,02	-73,81	-88,61	-62,31
Element-3	N	2778,46	2810,46	2743,00	2755,00	2774,17	2806,17	2717,25	2749,24
	V	-12,32	12,32	-1,66	1,66	-14,37	14,37	-1,77	1,77
	M	-33,77	15,53	-6,65	0,00	-36,48	20,98	-7,09	0,00

Table 8 Internal forces of considered frame system under vertical loads and landers earthquake

Element No	Internal Forces	G+Q+Ex				G+Q+Ey			
		Fixed Based Model		Isolated Based Model		Fixed Based Model		Isolated Based Model	
		i	j	i	j	i	j	i	j
Element-1	N	1825,38	1793,38	1800,04	1768,04	1788,26	1756,26	1767,52	1735,22
	V	10,55	-10,55	1,47	-1,47	6,03	-6,03	1,06	-1,06
	M	19,00	-23,18	0,00	5,87	7,62	-16,48	0,00	4,94
Element-2	N	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	V	98,43	-89,53	100,66	-87,44	99,39	-90,66	101,57	-63,21
	M	-87,03	-71,30	-86,75	-60,14	-89,44	-74,23	-89,08	-88,66
Element-3	N	2780,34	2812,34	2722,99	2754,99	2775,98	2807,98	2719,26	2751,26
	V	-12,34	12,34	-1,66	1,66	-14,48	14,48	-1,71	1,78
	M	-33,81	15,54	-6,65	0,00	-36,59	21,40	-7,11	0,00

Table 9 The quantities of materials are consumed for construction of both models

Materials	Fixed Model	Isolated Model	Rate of Profit (%)
Mould (m^2)	12268,14	11641	10
Concrete (m^3)	2044,05	2257,45	6
Reinforced (ton)	217,231	204,577	6

5. Conclusions

The aim of this study is to investigate effectiveness of seismic isolation system on a hospital-type structure of high ductility level in terms of dynamic behaviors. For this purpose, a nine-story hospital-type building was modelled by ideCAD structural software as both fixed based and seismic isolated models. Rubber bearings are interposed between the base and foundation of the structure. Time domain linear dynamic analyses are carried out on both models of building using earthquake records in time domain (Kocaeli, Loma Prieta and Landers). The results of the dynamic characteristics, displacements and internal forces of both models are compared with each other to reveal the effectiveness of the base isolation system on dynamic behavior of structure. From the results of this study, the following observations can be made:

• Base isolation system lengthens the structural periods of structures. The results obtained from modal analysis can be examined in Table 4. Differences among structural periods for the first, the second and the third modes are 8.15%, 7.82% and 8.26% respectively. The main purpose of seismic isolation is to reduce seismic loads transferred to structures by lengthening structural period rather than improving the strength of structures against seismic loads.

• Maximum difference between relative floor displacements along *x* axis of the both models under earthquake loads is 48.8% on the first floor.

• Maximum difference between relative floor displacements along *y* axis of the both models under earthquake loads is 45.7% on the first floor.

• The results of relative floor displacements show that relative floor displacements gradually decrease along the height of the building in framed structures. Differences between relative floor displacements along *x* and *y* axis under earthquake loads are 1.20% and 0.60% respectively on the top floor.

• Seismic forces transmitted to superstructure are reduced significantly by lengthening structural period at base isolated systems, so lower internal forces occur at cross sections of structural elements. In this study, internal forces are obtained from time history analyses under earthquakes for a selected frame with three elements. The values of axial force, shear force and bending moment are obtained from Kocaeli, Loma Prieta and Landers earthquakes for elements 1-2-3 can be investigated in Tables 6, 7, 8.

• For the selected frame, the maximum difference between fixed and isolated models in terms of axial force is 3.23% at columns. This value shows us that base isolation system is not very effective on reducing axial forces at columns.

• For the selected frame, the maximum differences between fixed and isolated models in terms of shear forces are 87.25% at columns and 2.5% at beam. Seismic loads are transferred to columns at the rate of their stiffness. Shear forces at the columns of base isolated model are less than ones of fixed model since base isolation systems reduce seismic forces transferred to structure. G+Q combination is very effective about shear forces occurring at beams, so the differences between both models in terms of shear forces is very few such as axial forces at columns.

• For the selected frame, the maximum differences between fixed and isolated models in terms of bending moments are 100% at columns and 80.51% at beam. This values show that base isolation system is very effective on reducing bending moments at columns and beams.

• Seismic forces transmitted to superstructure are reduced significantly by lengthening structural period at base isolated systems, so lower internal forces occur at cross sections of structural elements.

• Isolator system reduces internal forces, therefore; the dimension of structural elements decrease, it has made the economic benefits as shown in Table 9. Thus total construction cost of the structure has been decreased almost 5.30%.

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