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Araştırma Makalesi

An Investigation on Seismically Isolated Buildings in Near-Fault Region

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ÖZET

In this study, the effects of far-fault, near-fault and pulse-type ground motions on a seismically isolated building were investigated. The 3-dimensional finite element model of the building was created in the SAP2000 software and the dynamic characteristics were determined numerically. Three different earthquake ground motion characteristics of 1999 Düzce Earthquake in Turkey were selected to evaluate the structural behavior. The record motions of the Mudurnu and Sakarya station were selected as far-fault ground motion. For near-fault ground motion, 1999 Düzce Earthquake Düzce and Lamont 1062 station records were selected. 1999 Düzce Earthquake Bolu and IRIGM 487 station records were selected as pulse-type ground motion. The behavior of the building supported by friction pendulum isolators with a displacement capacity of 48 cm was compared with the analysis results of fixed-base building. The displacement values of the 1st, 4th and 7th floors of the building were obtained. The effects of earthquake ground motions and isolator were evaluated according to floor displacement values. The seismically isolated building has a less structural demand depending on the vibration mode period under pulse-like near-fault ground motions.

I. INTRODUCTION

Earthquake ground motions are affected by the earthquake magnitude, topographic features, and the geological structure of the ground, as well as the distance of the area under the earthquake to fault. The ground motions close to the fault are quite different from ground motions away from the seismic source. The ground motions, which are at about 20 km from the rupture are generally named as near-fault (NF) ground motions [1-4].

Some recent earthquakes like as Northridge 1994, Kobe 1995, 1999 Chi-Chi etc. are known as a short-duration impulsive motion that exposes the structure to high input energy at the beginning of the motions [5]. These motions have velocity pulse amplitude. This specialty cannot be seen in records obtained far-field (FF) regions [6]. The velocity pulse duration must be larger than 1.00 second and also the ratio of the peak ground velocity (PGV) to the peak ground acceleration (PGA) must be larger than 0.10 second [7].

Two main categories of the NF ground motions are fling-step and forward-directivity, respectively. The fling-step motions cause permanent static displacement in ground, whereas directivity effects do not create permanent displacement. Comparison to the FF ground motions, directivity- effects having the long-period and high-density and the fling-step effect causing permanent static ground displacements, are destructive for structures [8].

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In recently, much scientific research has focused on seismic response of the buildings in NF regions. According to a building severely damaged during 1971 San Fernando earthquake, analytical studies of the non-linear dynamic response of single and multiple degree-of-freedom systems to several NF records indicate that very large displacement ductility may result for current levels of code design forces [9]. The nonlinearity of a buildings is very sensitive to the pulse duration relative to the fundamental period as well as to the pulse acceleration relative to the yield resistance seismic coefficient [10]. Such motions cause damage to the structure as well as to its contents, decreasing the probability that the structure can remain functional after the earthquake. Reduce impact of these motions require exceptional design measures for isolation system [11]. For higher PGV/PGA ratio, pulse-like motions do not contribute too much to higher-modes, but relatively low PGV/PGA ratio fairly contributes. For high-rise buildings, pulses in ground motion records do not always contributes from higher modes [12]. Seismic response of SDOF systems or MDOF frame structures built near source region showed that code-prescribed story shear strength patterns lead to a highly non-uniform distribution of ductility demands over the height. For long-period structures, early yielding occurs in upper stories, but also in high ductility occur in bottom stories of low-period structures [13]. If moment-resisting frame structures is strengthened with hinged walls against NF effects, it will be master factor in reducing drift demands at various performance levels [14]. Forward-directivity effects show more instances of higher-mode demand of buildings, but fling-step displacement frequently caused fundamental mode. Ratio of motion pulse to natural period ensure design demand [15]. Retrofitting by using FRP improved stiffness, strength and lateral displacement capacity of structures against to fling-step effect [16]. According to the seismic response of multi-story buildings subjected to NF earthquakes, records with forward-directivity effect induce higher ductility demand compared with ordinary records [17]. The studies on behavior of steel frames subjected to the forward-directivity effect presented that NF motions motivate high modes of the structure, and high response is especially detected [18]. The results of the study on buckling-restrained braced frames showed that NF records caused to higher demands on the structures. Results for fling-step and NF records are very scattered, but in some cases these records have more damages on structure than the others. Reinforced concrete buildings subjected to large deformation requirements under the presence of velocity pulses in velocity time history. In these cases, a considerable amount of energy is needed to be dissipated in one or more cycles of plastic limit. Although, on average, deformation demands are less than those in the NF records, structural systems are subjected to more plastic cycles. Therefore, the cumulative effects of FF records are minor [19]. The behavior of the reinforced concrete buildings subjected to fling-step effect presents that the ratio of the fundamental period to the pulse period plays an important role [20]. Tuned mass damper (TDM) used to mitigate the dynamic response of buildings subjected to FF and NF earthquake showed that more seismic demand are necessary on an induced response for buildings excited by fling-step effect. In addition, soil effect increases the induced responses and alters the role of TMD in reducing the superstructure responses. TDM provide the highest dissipated damping energy for fling effects compared to forward-directivity effects and FF records [21]. To determinate of the effects of NF ground motions, the authors study on nonlinear response of core-wall buildings [22]. The researchers emphasized that higher mode effects increase when the first mode sensitive region moves away from the second mode sensitive region. Additionally, the ratio of pulse period to natural vibration period caused the elongated first mode period under large pulses in NF region. The seismic response of nonlinear masonry structures under NF and FF ground motions showed that NF ground motions may significantly damage the structure than FF ground motions [23]. Nonlinear analysis on efficiency of floor systems showed that response demand was increased under fling-step compared to forward-directivity which leads to more severe damage to buildings [24]. According to an investigation on behavior of the regular and irregular structures subjected to directivity effects, the high-frequency quantity should not be ignored since it may be thought that the resonance phenomenon occurs at $T_P/T_1=1$ (the ratio of pulse period to first mode period) [25]. In this situation, designers will have two choices: decomposing NF records to their high-or low-frequency components applying the dominant component based on the T_P/T_1 value and using the original ground motions.

In these days, seismically isolation systems have been used for many structures. Quaranta and Mollaioli investigated the use of the equivalent linearization for oscillators to estimate the peak displacement subjected to NF pulse-like earthquakes. The results of the analysis showed how the predictive ability of the equivalent linear model depends on the ratio between the elastic period of the ground motion and the impact period. Furthermore, the results show that the proposed correction leads to more robust and accurate predictions, especially for low cure rate values and medium-large impact times [26]. Wang et al. investigated the seismic responses of an isolated bridge with lead rubber bearing under NF ground motions [27]. Hysteretic models of lead rubber bearings are used to execute nonlinear time history analysis. Results indicate that the reactions of seismically isolated bridges are significantly influenced by ambient temperature, initial displacement, and lead core heating. Sodha et al. studied on a nonlinear mathematical model and seismic response of a structure isolated with Quintuple friction pendulum bearing under FF, NF ground motion with directivity effect and fling step effect. Analyses result indicated that the NF ground excitations for a given earthquake event might differ significantly from FF ground excitations depending on the directivity impact and rupture pattern [28]. Yi et al. proposed a tie-down cable-spring restrainer (TCR) that was effective in NF and FF earthquake excitations. A design procedure is proposed for the application of TCR to a lead-rubber bearing structure. The analysis results show that the seismic isolation system was protected from excessive displacement under major earthquakes. In addition, the results of the analysis showed that structures with TCR exhibit less sensitivity to NF ground excitations [29]. Abbaszadeh et al. investigated the performance of friction dampers and LRB isolators under various earthquake loads. The structure used was subjected to three sets of NFs, with pulse, NF, and FF records. The analysis results showed that the hybrid control strategy was the most efficient technique for NF with pulse, NF, and FF records [30]. A mega-sub isolation system's seismic response to NF ground motions with velocity pulses were evaluated by Li et al. [31]. SAP2000 was used to carry out the finite element study of the mega-sub fixed and seismically isolated. Analysis findings indicated that NF ground excitations with velocity pulses had a detrimental effect on the mega substructure system's seismic responses.

In the presented study, it is aimed to determine how seismically isolated buildings behave under NF motions and ordinary FF motions. For this reason, the seismic response of a 7-storey building was investigated under NF and ordinary FF motions take into consideration above-mentioned literature survey and information. Three different ground motion characteristics of 1999 Düzce Earthquake were selected to evaluate the structural behavior. The behavior of the building supported by friction pendulum isolators with a displacement capacity of 48 cm was compared with the analysis results of fixed-base building.

II. THEORETICAL METHOD

2.1 Earthquake Motion

The effects of strong ground motions on the structures depend on variables such as the amplitude, duration, and frequency content of the ground motion, as well as the mass of the structure, the natural period, damping, and stiffness. In this manner, the fault zone might drastically affect structural behavior. The ground vibrations that take place within 20 km of the rupture are defined as NF ground motions [32-35]. The velocity pulse duration must be larger than 1.00 seconds. The ratio of the PGV to the PGA must be larger than 0.10 seconds [36]. The NF ground record motions have long-period pulses and permanent ground displacements which are not visible in recordings gathered in FF regions [37].

In this manner, ground motions can be categorized as having or not having a pulse signal in the near regions. Because it is simpler to recognize the pulse from the velocity waveforms, they are used to identify the pulse signals [38]. Velocity time series were given in Figure 1 for comparing the NF ground motion with and without a pulse signal.

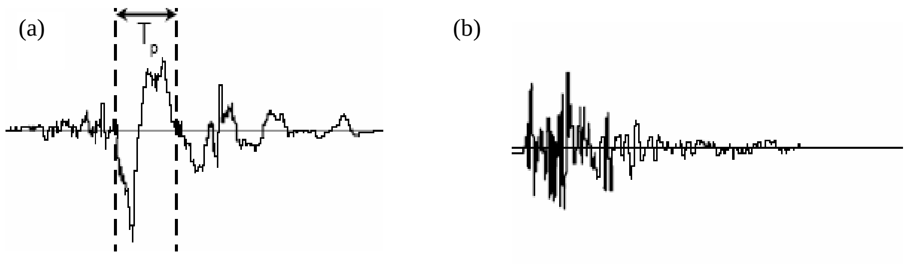

Figure 1. Velocity time series with a pulse (a) and without pulse (b) signals

Fundamentally, the important response parameters for the structures are the peak ground displacement (PGD), PGV, and PGA. The NF ground motions have a high PGV/PGA ratio, which significantly impacts their responses [39]. As long as the pulse amplitude and duration increase, the displacements and drift demands will increase. If NF ground motions compared to FF ground motions, the velocity-sensitive spectral region for NF recordings is substantially narrower, while the acceleration-sensitive and displacement-sensitive sections are much wider. For the same ductility, NF ground motions required a greater strength demand than FF ground motions. If the periods were normalized to the acceleration-sensitive region transition period, the response may become similar for the motions in both near and far regions [40].

In the present study, a seismically isolated building was subjected to two types of ground motion records, which are NF ground motion having different pulse durations and ordinary FF records. The period of the pulse (extracted pulse, T_p) is identified as the time needed to complete a full velocity cycle and is obtained in the velocity time history of the selected ground motions. Besides, every record set given in Table 1 which contained two types of NF and one type of FF earthquake motion.

Table 1. Dynamic characteristics of selected ground motions

RSN	***Motion Type***	***Event Name***	***Station***	R_{rup} *(km)*	***PGA*** *(cm/s²)*	***PGV*** *(cm/s)*	T_p *(sec)*
1619	FF1	Duzce, Turkey (1999)	Mudurnu	34.3	90.25	13.28	-
1620	FF2	Duzce, Turkey (1999)	Sakarya	45.2	21.58	5.02	-
1605	NF1	Duzce, Turkey (1999)	Duzce	6.58	425.75	78.70	-
1615	NF2	Duzce, Turkey (1999)	Lamont 1062	9.14	203.07	14.63	-
1602	PLS1	Duzce, Turkey (1999)	Bolu	12.04	761.26	62.90	0.88
8164	PLS2	Duzce, Turkey (1999)	IRIGM 487	2.65	286.45	32.85	10.05

In addition, the original acceleration time history and velocity time history of selected motions are given in Figure 2 and Figure 3, respectively.

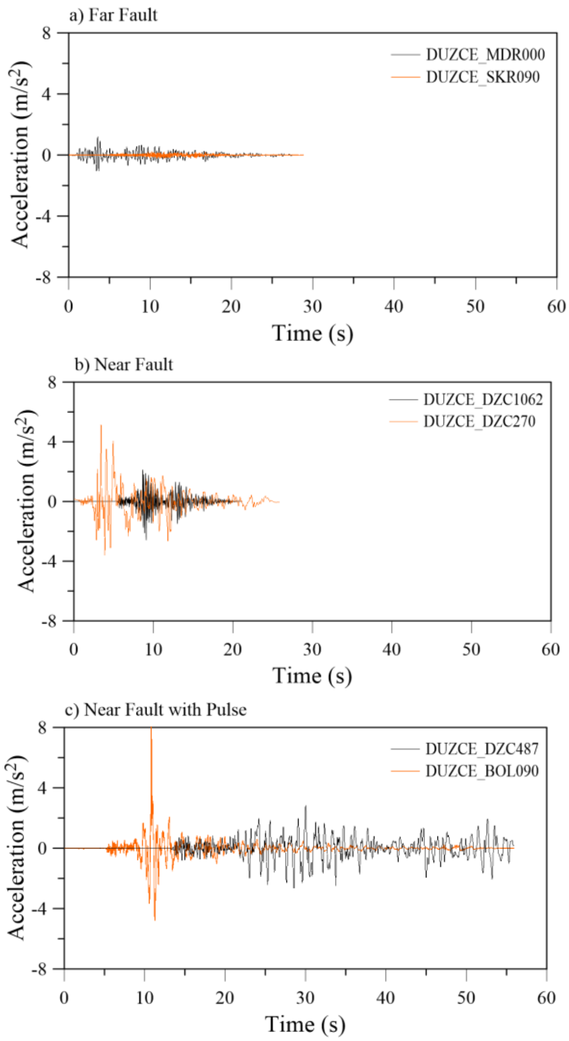

Figure 2. Acceleration time histories of the selected motions

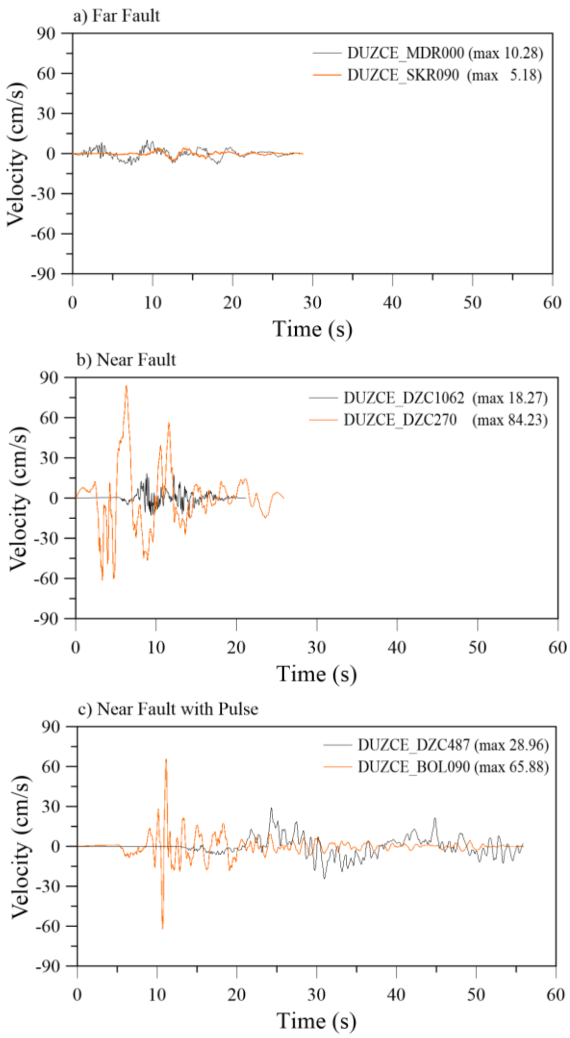

Figure 3. Velocity time histories of the selected motions

2.2 Seismic Isolation System

In this study, the building was isolated with friction pendulum bearing (FPB) system. Six different FPBs with a 48 cm displacement capacity were designed in the study. The building's overall weight was 72436 kN. The FPB was designed considering that the building is in a place with a ZC soil class according to TBEC-2018 [42] in Düzce, Turkey. An iteration is carried out to design the displacement of the FPB. The friction coefficient between sliding surfaces (μ_e) is 0.096, effective radius (R_e) is 4.5m, and yielding displacement (D_y) is 0.48m.

Effective stiffness, K_{eff} and estimated isolator displacement, D, are calculated by Eq. 1,

$$K_{eff} = \frac{P}{R_e} + \frac{\mu_e}{D} \tag{1}$$

where, P is the total weight of building. Effective damping coefficient (β_{eff}) of the FPBs is calculated by Eq. 2. The value of β_{eff} is limited to 30% (TBEC 2018).

$$\beta_{eff} = \frac{2}{\pi}\frac{\mu_e}{\frac{D}{R_e}+\mu_e} \quad (2)$$

Damping scaling factor (η) is calculated by Eq. 3.

$$\eta = \frac{10}{5+\beta_{eff}} \quad (3)$$

Period of the FPB_S is calculated by Eq. 4.

$$T = 2\pi\sqrt{\frac{P}{g\times K_{eff}}} \quad (4)$$

The spectral acceleration (S_a) is calculated by Eq. 5.

$$S_{a(g)} = \frac{S_{ae}}{\eta} \quad (5)$$

S_{ae} is the value corresponding to the period in the determined horizontal elastic earthquake spectrum. Spectral displacement (S_d) is calculated by Eq. 6.

$$S_d = \left(\frac{T}{2\pi}\right)^2 S_{a(g)} \quad (6)$$

If the S_d is less than the estimated isolator displacement, the iteration is terminated. Effective stiffness of horizontal directions of FPBs for linear analysis is calculated by Eq. 7.

$$K_{effli} = \frac{P_i}{R_e} + \frac{\mu_e P_i}{D} \quad (7)$$

P_i is load supported by FPB (i=1,2,…6). Effective stiffness of horizontal directions of FPBS for nonlinear analysis is calculated by Eq. 8.

$$K_{effnli} = \mu_e \frac{P_i}{D_y} \quad (8)$$

The design parameters of FPBS were given in Table 2.

Table 2. The design parameters of FPB

Isolator Type	μ_e	R_e	P_i (kN)	D_y (m)	D (m)	K_{effli} (kN/m)	β_{eff}	K_{effnli} (Nonlinear)
A	0,096	4,5	1450	0,00254	0,48	1172	0,3	54803
B	0,096	4,5	2087	0,00254	0,48	1687	0,3	78879
C	0,096	4,5	2116	0,00254	0,48	1710	0,3	79975
D	0,096	4,5	3067	0,00254	0,48	2479	0,3	115918
E	0,096	4,5	3110	0,00254	0,48	2514	0,3	117543
F	0,096	4,5	3155	0,00254	0,48	2550	0,3	119244

2.3 Structure Description and Modeling

A seven-story building was selected for dynamic analysis. The building to be analyzed is designed with a 1-5 axis in x-direction and A-F axis in y-direction. The axis distances in both directions of the building are 7 meters. Plan view and 3-D finite element model of the building are given in Figure 4 and Figure 5. A reinforced concrete frame system is used as the structural system. The slab plate was chosen as the slab type. Column with dimensions of 80x80 cm, beam with dimensions 40x70 cm, and floor slab with thickness 15 cm. The story height of the building is 400 cm. The live load of 5 kN/m^2 and dead load of 1 kN/m^2 according TSC [41]. The unit volume weight of reinforced concrete with 25 kN/m^3 and the unit volume wall weight with 4 kN/m were selected.

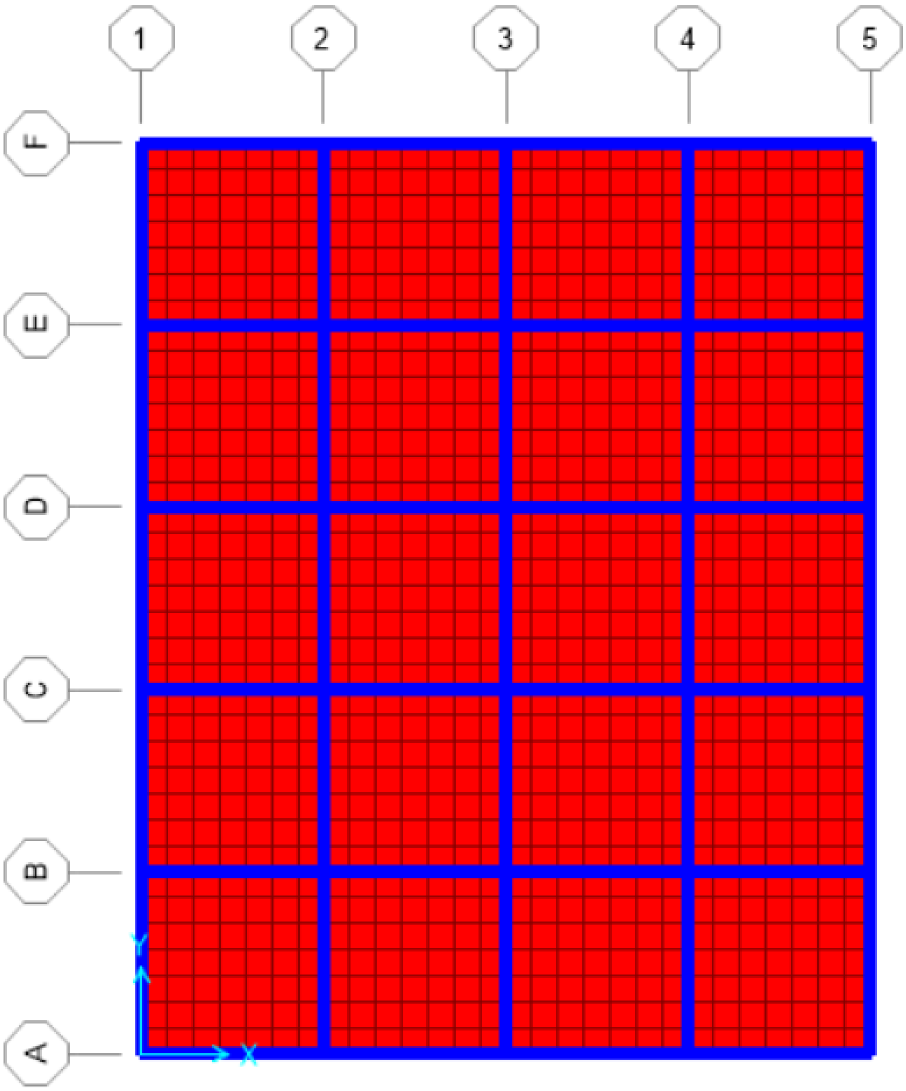

Figure 4. Plan view of the building

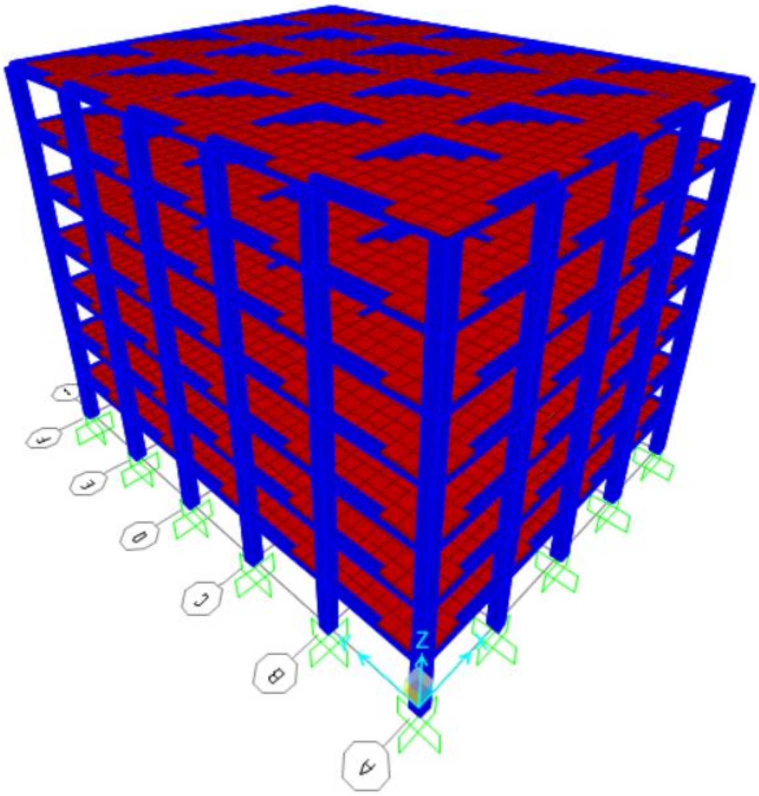

Figure 5. 3-D finite element model of the building

The first three mode shapes obtained from numerical modal analysis of the building are presented in Figure 6. As shown in Figure 6, the first two modes are translational modes along with the two main directions of the building. The first mode is translational in the X direction while the second one is translational in the Y direction. The third mode is a torsional mode for building.

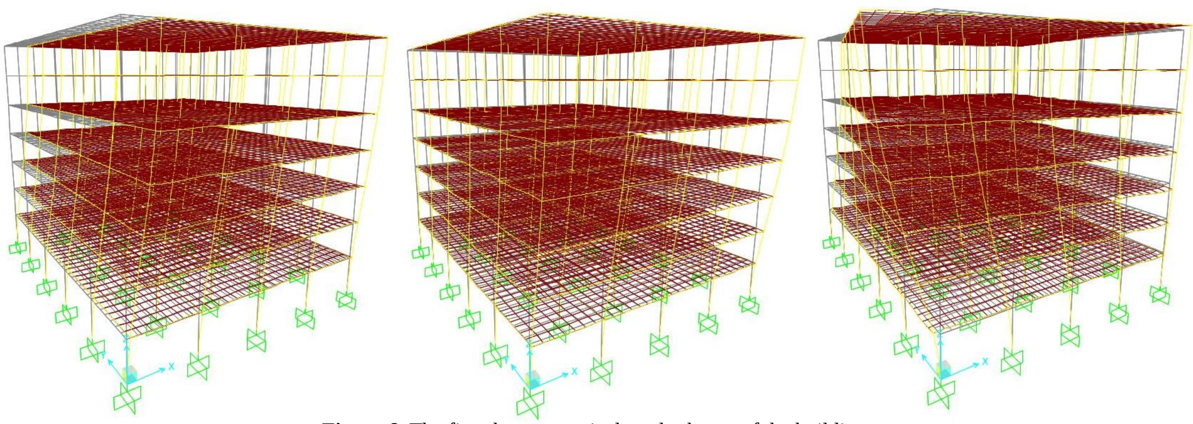

Figure 6. The first three numerical mode shapes of the building

The modal analyses were carried out considering the first 15 modes to check the effect of modal masses. The periods of first three vibration mode were given in Table 3.

Table 3. The periods depend on the mode shapes of the considered models

Models	***Fundamental Period (s)***		
	1st Mode	***2nd Mode***	***3rd Mode***
Fixed base	0.9898	0.9749	0.8656
Isolated base	2.5457	2.4248	0.4850

III. RESULTS AND DISCUSSIONS

The earthquake analysis of the building was performed to investigate the near and FF effects on the seismically isolated buildings. The relationship between the lateral displacements of the first floor x-direction under earthquake motions is given as time history in Figure 7.

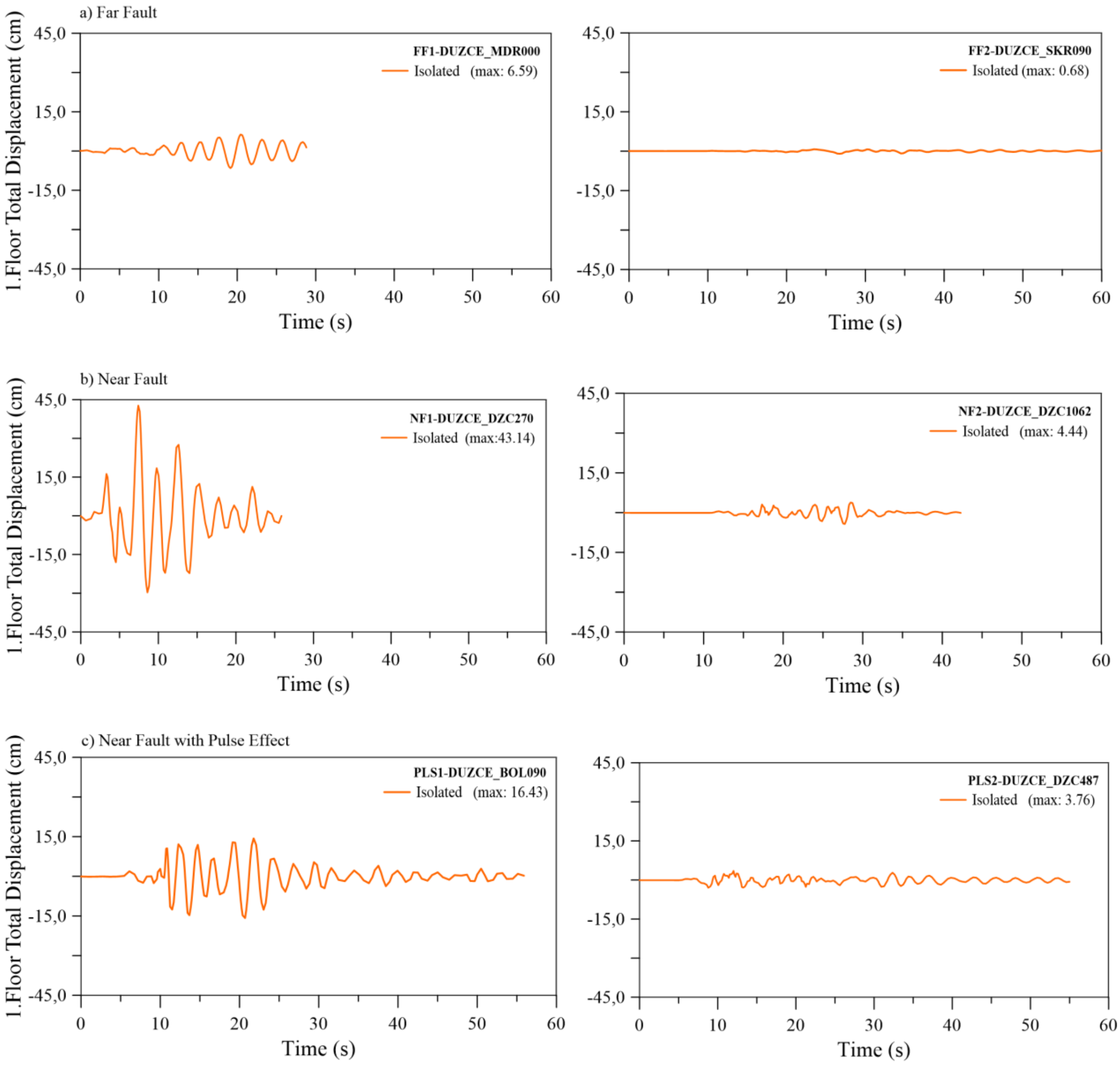

Figure 7. Total displacement-time history of first floor with isolated base

As mentioned above, the total displacement capacity of the isolators was calculated as 48 cm. The displacements obtained from the seismically isolated building subjected to FF1 ground motion was 6.59 cm and FF2 ground motion was 0.68 cm at the 1st floor, respectively. The 1st floor displacements subjected to NF1 ground motion was 43.14 cm and NF2 ground motion was 4.44 cm, respectively. The 1st floor displacements of the building subjected to PLS1 was 16.43 cm and PLS2 was 3.76 cm, respectively. Although the ground motion recorded at Bolu Station has a large PGA and pulse content, large displacement was obtained from Düzce Station.

The fourth-floor displacements on x-direction under considered earthquake motions were given as a time history in Figure 8. The displacements obtained from the seismically isolated building subjected to FF1 ground motion was 7.44 cm and FF2 ground motion was 0.77 cm at the 4th floor, respectively. The 4th floor displacements subjected to NF1 ground motion was 48.72 cm and NF2 ground motion was 5.01 cm, respectively. The 4th floor displacements of the building subjected to PLS1 was 18.51 cm and PLS2 was 4.07 cm, respectively.

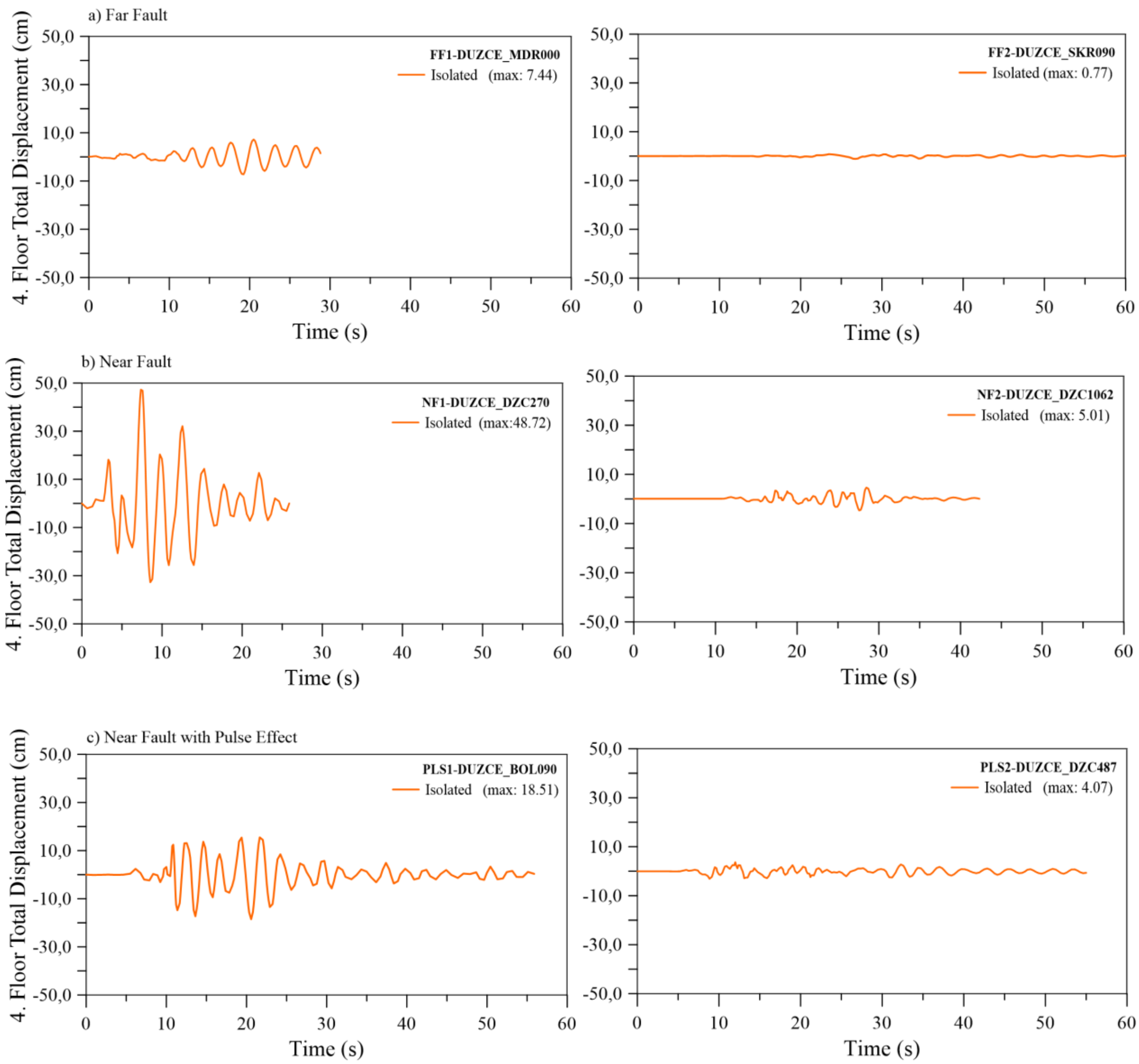

Figure 8. Total displacement-time history of fourth floor with isolated base

The displacement time history for the seventh floor on x-direction were given in Figure 9 for considered earthquake motions. The displacements obtained from the seismically isolated building subjected to FF1 ground motion was 7.84 cm and FF2 ground motion was 1.26 cm at the 7^{th} floor, respectively. The 7^{th} floor displacements subjected to NF1 ground motion was 51.40 cm and NF2 ground motion was 5.27 cm, respectively. The 7^{th} floor displacements of the building subjected to PLS1 was 19.49 cm and PLS2 was 4.09 cm, respectively.

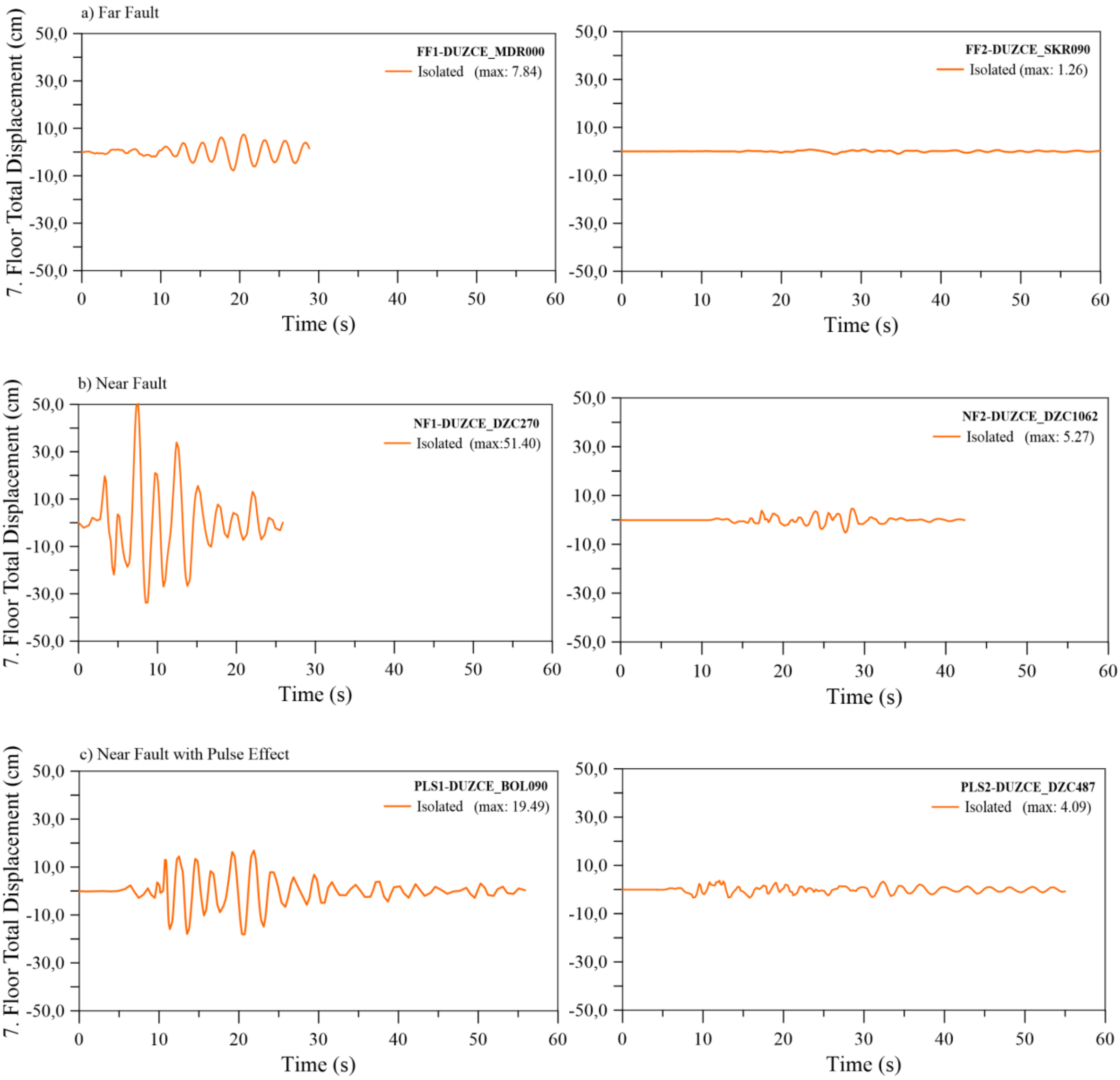

Figure 9. Total displacement-time history of seventh floor with isolated base

Relative floor displacements were obtained by subtracting the total storey displacement values from the building base displacement. The base displacements were equal to isolator displacement for the isolated building. The relative storey displacements at 1^{st} floor were given in Figure 10. The 1^{st} floor displacement under FF1 ground motion for the fixed and isolated building were 0.28 cm and 0.18 cm, respectively. The displacement under FF2 ground motion for the fixed and isolated building were 0.08 cm and 0.03 cm, respectively. The 1^{st} floor displacement under NF1 ground motion for the fixed and isolated building were 2.73 cm and 1.21 cm, respectively. The displacement under NF2 ground motion for the fixed and isolated building were 0.67 cm and 0.12 cm, respectively. The displacement under PLS1 ground motion for the fixed and isolated building were 4.09 cm and 0.40 cm, respectively. In addition, the displacement under PLS2 ground motion for the fixed and isolated building were 0.89 cm and 0.10 cm, respectively.

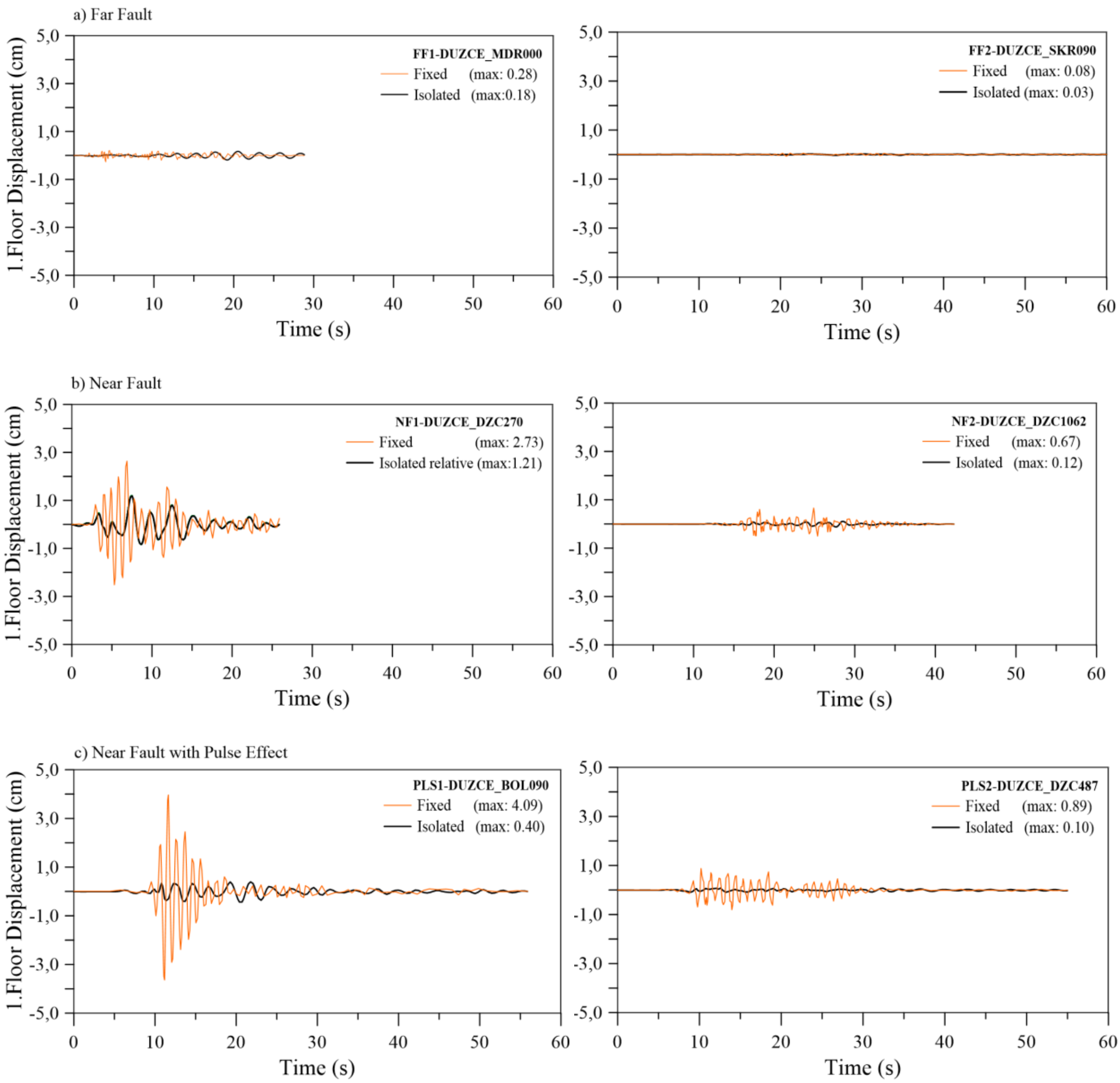

Figure 10. Relative displacement-time history of first floor

Relative displacement of fourth floor were given in Figure 11. The displacements were 1.23 cm and 1.00 cm for fixed-base and isolated buildings under FF1 ground motion, respectively. The displacements were obtained as 0.39 cm and 0.17 cm for fixed-base and isolated buildings under FF2 record motion, respectively. For the NF1 and NF2 motions, fourth floor displacements were obtained as 16.84 cm-6.80 cm and 3.73 cm-0.76 cm for the fixed base and isolated base, respectively. If considered the pulse-type ground motion, PLS1 caused to 25.01 cm displacement for fixed-base building and 2.54 cm displacement for isolated building. In addition, the displacements were obtained as 5.24 cm for fixed-base and 0.66 cm for isolated under the PLS2 motion.

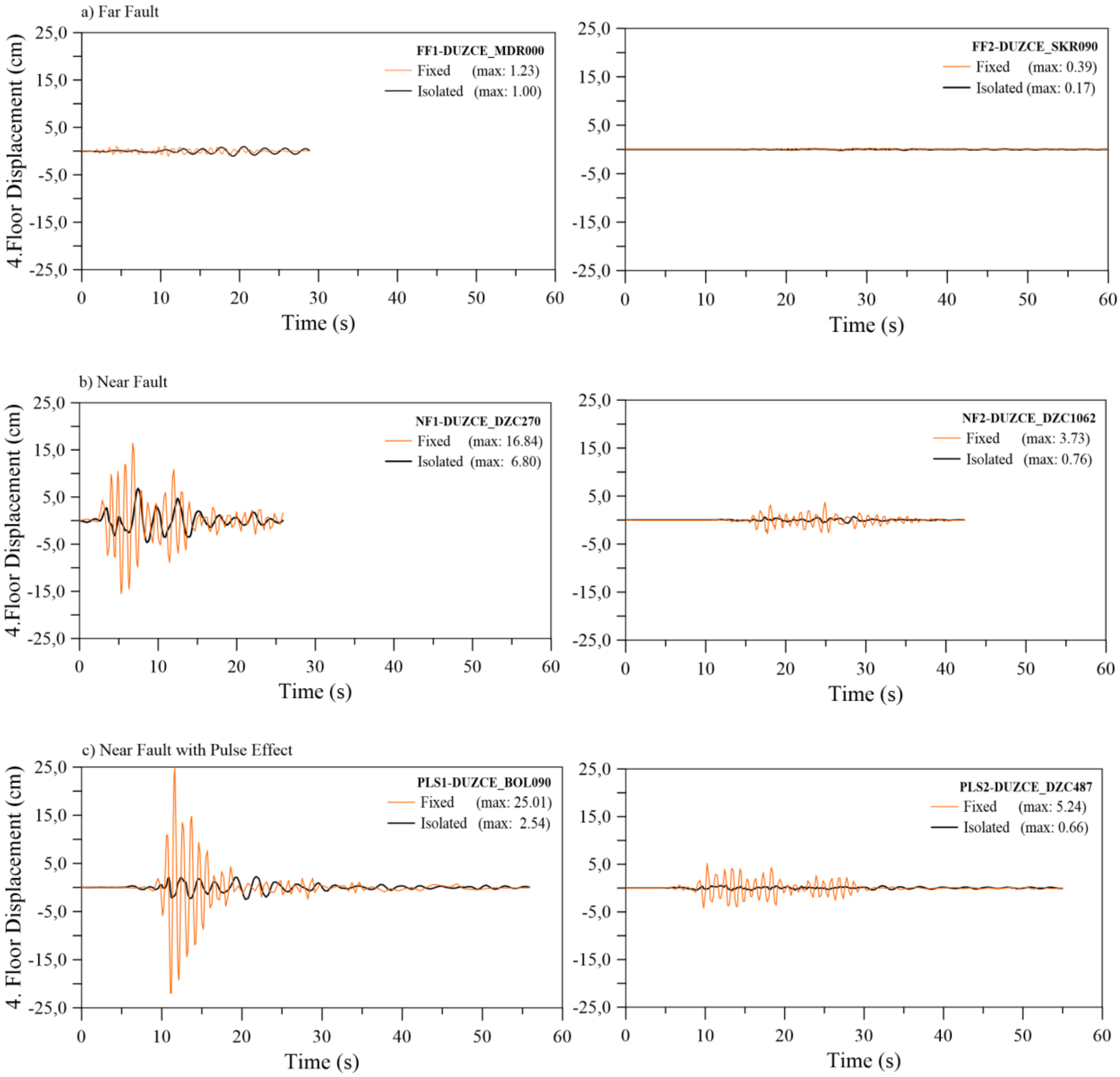

Figure 11. Relative displacement-time history of fourth floor

As seen Figure 12, the maximum displacements of seventh floor were 1.89 cm and 1.39 cm for fixed-base and isolated buildings for FF1 ground motion, respectively. The maximum displacements were obtained as 0.49 cm and 0.24 cm for fixed-base and isolated buildings under FF2 record motion, respectively. Seventh floor displacements were 24.39 cm-9.51 cm and 6.63 cm-1.13 cm for the NF1 and NF2 motions, respectively. If considered pulse-type ground motion, PLS1 caused to 36.13 cm at seventh floor level in fixed-base building and 3.55 cm displacement for isolated building. In addition, the seventh floors of fixed-base and isolated building displaced as 8.04 cm and 1.11 cm under the PLS2 motion, respectively.

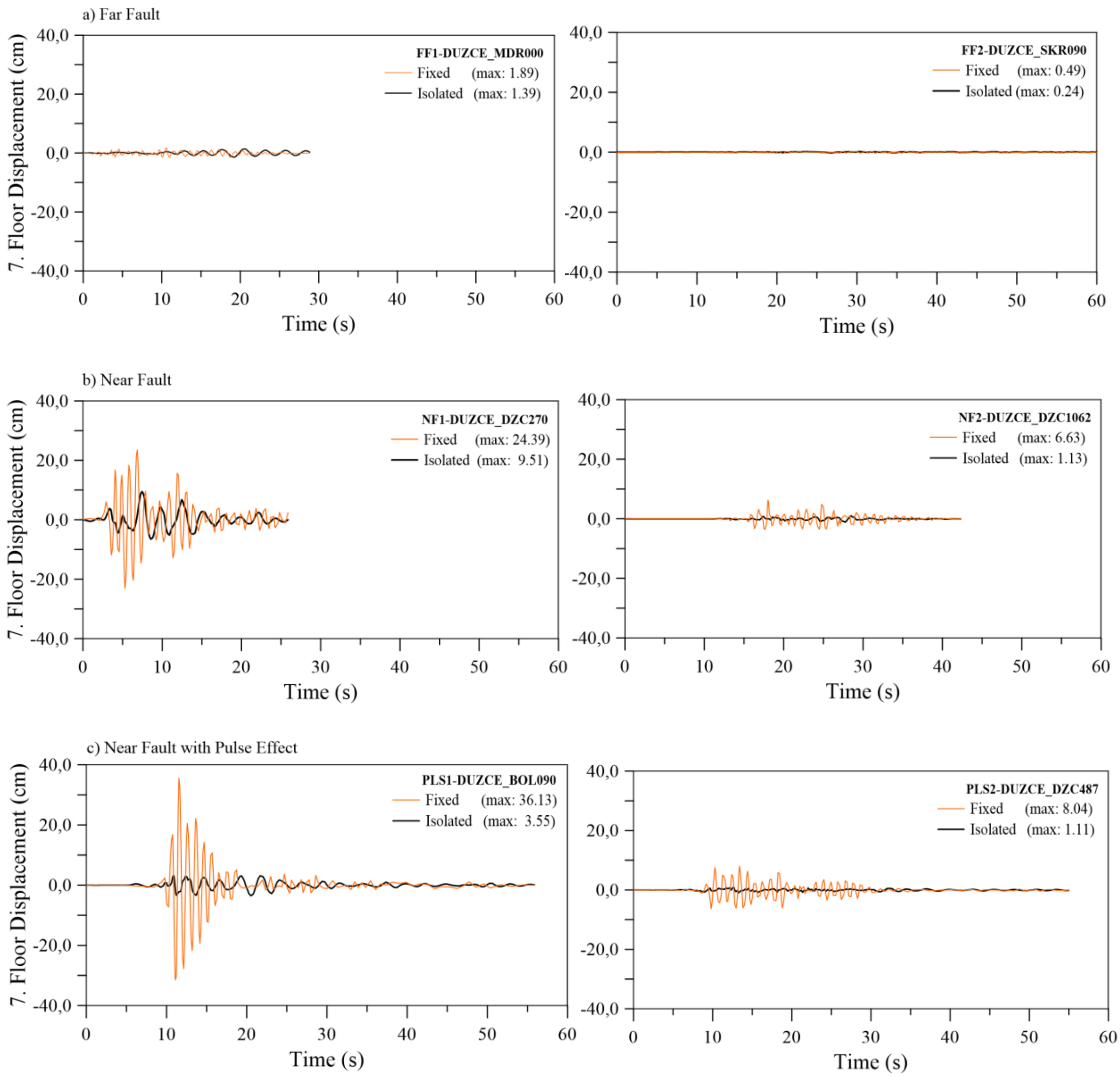

Figure 12. Relative displacement-time history of seventh floor

IV. CONCLUSIONS

One of the most important solutions developed to increase the earthquake performance of the buildings within the earthquake fault zone is using of the base isolator with high damping capacity between the building and the foundation. In order to reduce the earthquake loads acting on the buildings, base isolators have been frequently used especially in high-rise buildings for many years. Although structural demands decrease in the seismically isolated buildings, the structural behavior of the isolated buildings under different earthquake characteristics should be well known. In this study, the dynamic behavior of the seven-storey isolated building was investigated for NF and FF ground motions. Dynamic analysis was performed with SAP 2000 finite element analysis software. For evaluation of the structural behavior, three different earthquake ground motion characteristics were selected. 1999 Düzce Earthquake was chosen as main ground motion. Mudurnu and Sakarya station records of 1999 Düzce Earthquake were selected for FF ground motion. Düzce and Lamont 1062 station records of 1999 Düzce

Earthquake were considered NF record motion. As a pulse-type record motion, 1999 Düzce Earthquake Bolu and IRIGM 487 station records were selected. The structural behavior of the building supported by friction pendulum isolators with a displacement capacity of 48 cm was compared with the analysis results of fixed-base building. The following results were obtained in the study:

- Although the PGA is the most effective parameter for all buildings, isolated buildings were mostly affected under PGA of record motion compared to fixed-base buildings for FF earthquakes and non-pulse-like NF earthquakes.
- If the isolated building is subjected to pulse-like NF ground motion, the isolated building will have less structural demand depending on the vibration mode period.
- Fixed-base buildings have high structural demand both the PGA of ground motion and pulse effect.
- The distance of an earthquake ground motion from the structure is not the only dominant parameter for the structural behavior.
- The seismic isolation or damping mechanisms are a great valuable solution for the buildings under pulse effect of the strong ground motion.

In the light of the results, the seismically isolated buildings should be investigated under the pulse duration of the ground motions in the future studies considering the nonlinearity and utilization of other damping mechanisms. High mode effects and pulse period effects should be evaluated for the seismically isolated buildings.

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