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Determination of Earthquake Behaviors of a Reinforced Concrete Building with and without Earthquake Base Isolation

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ABSTRACT

There are many fault lines within the borders of our country, especially the North Anatolian Fault line. For this reason, earthquake resistant structural design is a very important issue in order to prevent possible economic losses after earthquakes, especially the life safety of people living in our country. The main goal in earthquake insulation, which is a new approach in earthquake design of buildings, is to reduce the possible effects on the structure by placing flexible elements in the horizontal direction and rigid in the vertical direction, by greatly reducing the earthquake loads and accelerations acting on the superstructure. In this study, the earthquake behavior of the buildings, which were designed by the Housing Development Administration of the Republic of Turkey and designed as a base isolation support, and the structures designed according to the principles determined in the Turkey Building Earthquake Code 2018 by using base isolation, were determined according to the non-linear time history analysis method. The behavior changes of the structure designed using earthquake base isolation compared to the conventional structure were examined, and the period values, floor accelerations and base shear forces of the two structures were compared. As a result of the results obtained, the positive effects of the period increase and the decrease in floor accelerations in the earthquake insulated structure were revealed.

Keywords: Earthquake, Base Isolation, Non-linear time history analysis

INTRODUCTION

Earthquake, one of the most important natural disasters, because it is a vibration of the earth's crust, creates a dynamic effect by causing a time-dependent displacement movement on the supports of the structures. The study of this vibrational motion is one of the main problems of structural dynamics. One of the two important steps of earthquake resistant building design is to arrange the structural system of the building well, to ensure sufficient material quality and to construct it with care, and the other is to meet the cross-sectional effects expected to be created by the earthquake on the carrier system by determining with sufficient approximation (Celep, 2019).

When we examine the earthquakes that have occurred in the past years, the biggest parameter that causes damage to the structures is the insufficient deformation capacity of the carrier elements in response to the high displacement demand of the earthquake. In order to prevent this, what needs to be done is to cut the structure-ground relationship, to reduce the response of the structure to the earthquake demand and to prevent damage. Base isolation systems are used to meet the earthquake demand of the buildings and to absorb the energy without damaging the superstructure.

The basic philosophy of classical building design is to ensure the "life safety" of living beings. In other words, a certain amount of damage to the structure is deliberately allowed. In the earthquake design of structures, as in the worldwide regulations, the damage expectation in the Turkey Building Regulation which entered into force in our country in 2018;

- No damage to structural and non-structural elements in frequent earthquakes,
- Limited and repairable damage to structural and non-structural elements in less frequent earthquakes,
- In rare earthquakes, non-permanent damage to structural and non-structural elements and ensuring life safety.

With the developing technology, the continuation of use of the buildings after the earthquake and economic

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concerns have ceased to be an adequate design philosophy to ensure the life safety of only the contents of the structures. In this case, the design approach to be applied is performance-based structural design. In the said design philosophy, the necessary designs are made for a certain behavior under the influence of an earthquake instead of a predetermined behavior of the structure under the influence of an earthquake. Here, a certain design approach is made for the behavior of the non-bearing elements as well as the carrier elements according to the targeted behavior. With this approach, not only the damage to the carrier element, but also the loss of life and property due to the damage of the non-bearing elements can be prevented.

In previous studies on this subject, the earthquake behavior of the structures was investigated both with built-in foundations and earthquake insulation.

Tezcan and Cimilli (2002), investigated earthquake behavior by increasing the periods of structures using seismic isolators. In order to demonstrate the effects of seismic base isolation systems, a two-storey sample building was previously considered as built-in foundation and later with seismic base isolation, and behavioral analyzes were made with static equivalent earthquake loads and earthquake records in the selected time history area. They showed with examples that the structure with seismic isolation support shows better earthquake performance than the structure with built-in support.

Yücesoy (2005), dynamic analyzes were made by using selected acceleration records. In order to show the behavior of the structure with seismic isolators, the selected structure was modeled separately as both built-in foundation and insulated, and the effect of the isolators on the structure behavior was investigated. As a result of the analysis, the positive and negative effects of seismic isolation on the structure are explained comparatively.

Tolay (2006), made explanations as rubber-based and slippery systems from seismic isolation systems. He explained the theoretical basis, mechanical characteristics and modeling of seismic isolation systems. By considering two building models as base insulated and built-in, analyzes were made with Sta4Cad computer program and their costs were compared.

Karabork et al. (2010), compared the earthquake behavior results of two built-in support and earthquake-insulated structures designed on weak ground according to the selected earthquake record. They stated that the earthquake insulated structure showed better behavior under the effect of earthquakes.

Castaldo et al. (2015), stated that frictional base isolation units are a method that can be used both during construction and for strengthening methods in various building types with their physical and durability properties. He evaluated the earthquake safety of a building with base isolation using friction pendulum and stated that it is appropriate to apply base isolation in buildings.

Pekgokgoz et al. (2007), a 6-storey building, which is considered to be in the 1st degree earthquake zone, was analyzed separately as base isolation support and earthquake insulated and the total construction costs were calculated. Obtained results are presented comparatively.

In this study, both the earthquake behavior of the building, which was designed by the Housing Development Administration as a base isolation support, and the structure designed according to the principles determined in the Turkey Building Earthquake Code 2018, using earthquake insulation, were determined and comparisons were made.

In order to perform the analyzes of the structures in the Time History Domain; 11 sets of spectra compatible acceleration records (11×2=22 acceleration records) were selected from previous earthquakes. Dynamic analyzes in non-linear inelastic time history were carried out in the models with built-in support and earthquake isolation, by simultaneously acting the horizontal components of each selected earthquake set together in two horizontal directions perpendicular to each other. Then, the axes of the acceleration records were rotated 90 degrees and the calculation was repeated (TBDY, 2018). With the results obtained, the positive effects of earthquake behavior of earthquake insulated models compared to built-in support models have been revealed.

MATERIALS AND METHODS

In the base isolation structure design, in the Turkey Earthquake Code, 2018, effective earthquake load method, mode combination method and nonlinear calculation design methods in the time history is given. In the design of a structure with base insulation, different from the design principles of structures without base insulation, the effects such as the type of soil on which the building is located, the period of the building system, the number of floors and torsion should be taken into account. The displacements of the insulation unit calculated in the mode combination method and the time history should not be less than 80% of the displacement values calculated according to the effective earthquake load method.

Therefore, in this study, the insulation system was designed according to the effective earthquake load method and analyzes were carried out according to the non-linear method in the time history.

Identification and modeling of fixed supporting structure

The building, which has been applied by the Housing Development Administration and designed as traditional built-in support, is formed as B + Z + 5 N.K and has 7 floors. The floor height is 3.0 m for each floor. The total building height is 21 m. The floor area is 402 m^2. Since the building will be built with reinforced concrete and tunnel formwork system, it was built with no gaps. The formwork plan of the analyzed building is given in Figure 1 below. The thickness of the walls used is 20 cm, the columns have a cross-sectional area of 20×50 cm, and the tie beams have a cross-sectional area of 20×50, 20×60 and 20×80 cm. The floor heights of each floor are 14 cm, and the floor of the hall with wide openings is considered as 16 cm. For dead loads of the building; the external and internal wall loads were calculated as 4 kN/m, the normal floor slabs' covering load was 2 kN/m^2, the landing and stairwell covering load was calculated as 3.5 kN/m^2. For live loads, the general 2 kN/m^2 for the deck, 5 kN/m^2 for the balcony floors and 5 kN/m^2 for the landing and stairwell are taken into account. The properties and soil parameters of the materials used are given below.

Features of the material used:

Concrete class: C25/30 (fck =25 MPa)

Reinforcement class: S420 (fyk =420 MPa)

The structural load-bearing system was chosen as a wall system with a high ductility level, and the flooring system was determined as slab flooring. As can be seen in Figure 2, the 3D image of the structure, which was implemented and designed as earthquake insulated by rearranging the carrier system, was made with the ETABS finite element package program.

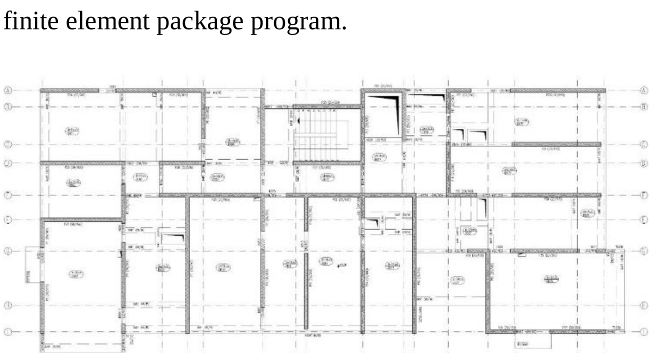


Figure 1. Formwork plan of the base isolation support structure

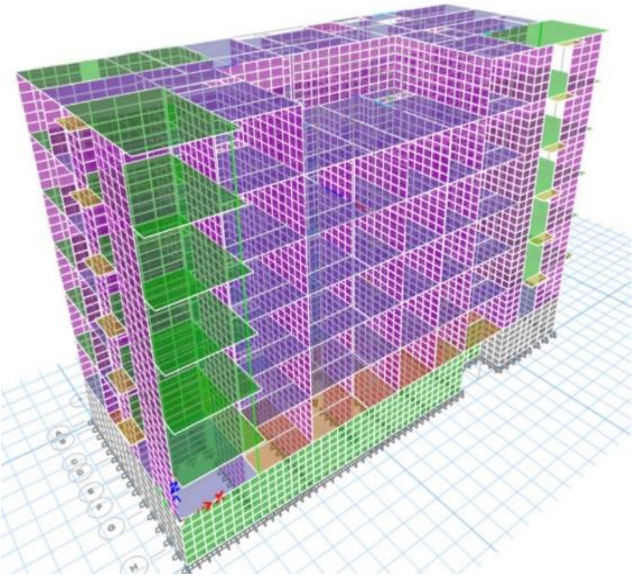


Figure 2. 3D view of built-in support structure

Obtaining the target spectra used for analysis

AFAD's earthquake hazard data were used to obtain the target spectrum to be used in the analysis. The necessary parameters for the target spectrum were obtained by entering the coordinates for the 41.1681° latitude and 27.85227° longitude of the Tekirdağ province Çorlu district, where the said structure was built, and the spectral data read for the target spectrum from the AFAD website are given below.

SD= 0.787 (Parameter of Short Period Map Spectral Acceleration)

S1= 0.216 (Parameter of Map Spectral Acceleration for 1 s period)

PGA=0.326 (Maximum ground acceleration)

PGV=20.113 (Maximum ground speed)

The 5% damped design acceleration spectrum for horizontal earthquake motion is given in the equations below depending on the design spectral accelerations, design spectral acceleration coefficients and natural vibration periods according to TBDY (2018).

SDS = SS x FS = 0.787 x 1.185 = 0.933

SD1 = S1x F1 = 0.216 x 2.168 = 0.468

Features of base isolation building

The entire load-bearing system of the building, which was designed by the Housing Development Administration and designed as a traditional built-in support, was changed without changing the external contour and loads. Base isolation units are placed on the basement ceiling of all columns in the building. All the shears in the building were removed and turned into a frame system, as it would cause separation in the insulation units by creating a tensile force in the insulation units in earthquake-insulated buildings. The mold plan and 3D image formed with the carrier system modified are as shown in Figures 3 and 4.

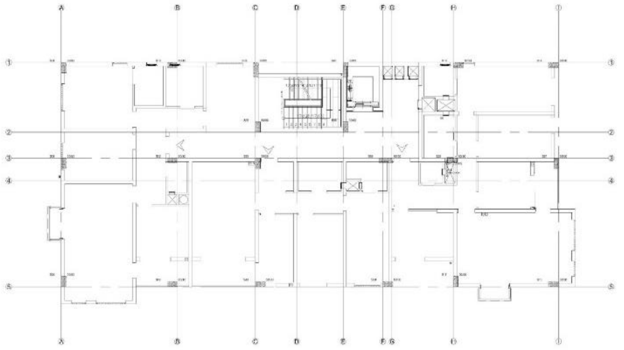


Figure 3. Formwork plan of earthquake insulated building

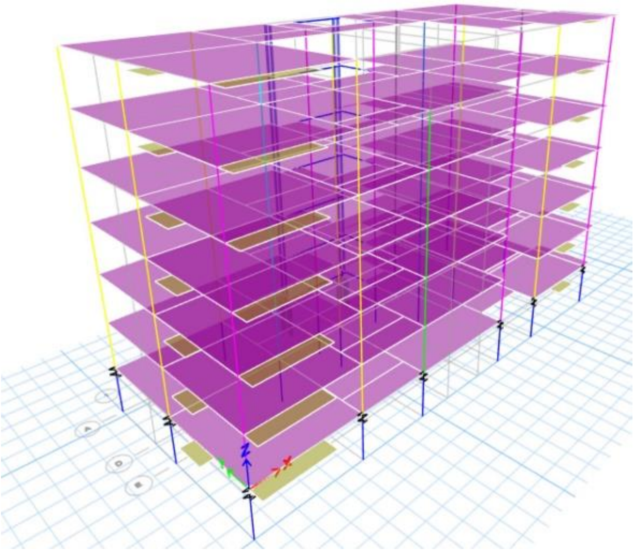


Figure 4. 3D view of earthquake insulated building

Base isolation element used

Base isolation application finds a solution to the problem of floor accelerations and relative floor displacements that will occur depending on the earthquake force at the same time. As seen in Figure 5, by decreasing the stiffness of the structure it is applied to, it extends its period and provides less earthquake load to the superstructure. With the effect of decreasing floor accelerations, besides the protection of the structural elements, the loss of property and life caused by the damage of non-structural elements is prevented. When possible inelastic displacements in the structure occur in the insulation layer, the superstructure makes a rigid mass movement and the relative storey drifts are limited. Since inelastic behavior in the structure is mostly caused by the relative store drifts, the use of seismic isolation prevents or limits the damage of the structure. With a properly designed insulation system, torsion that may occur due to the eccentricity of the superstructure can also be avoided. Torsional effects can be isolated from the structure by coinciding the insulation system with the rigidity system of the superstructure (Hoşbaş, 2006).

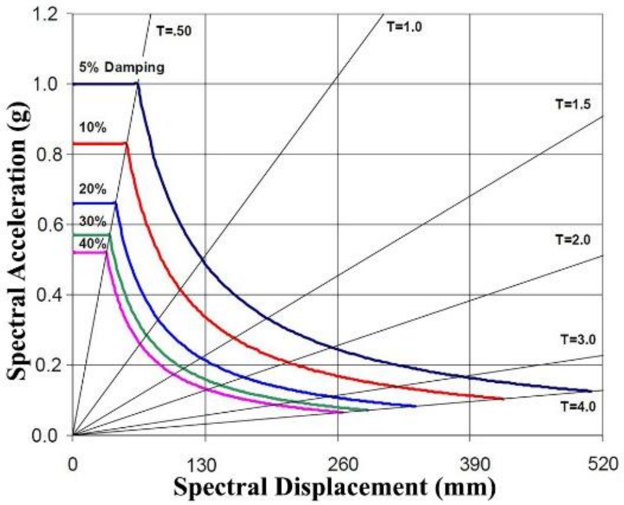


Figure 5. Damping & Acceleration & Displacement Relationship

Friction pendulum type insulation units (FPS), which is the type of base isolation unit used in this study, were used. In these systems, friction pendulum insulation units are insulation units that combine the centering force of the structure by using the friction coefficient and geometry of the system. The main principle is the energy dissipation of the Teflon-coated articulated slide (Figure 6), which moves on a spherical surface made of stainless steel, as a result of the friction force formed at the interface. The friction between the sliding element and the spherical stainless-steel surface provides damping. The effective stiffness of the insulating unit and the period of the structure depend on the curvature diameter of the spherical surface and are independent of the mass. During an earthquake, the simple pendulum movement with the effect of the insulation unit increases the period of the leaf structure and reduces the earthquake effect on the structure.

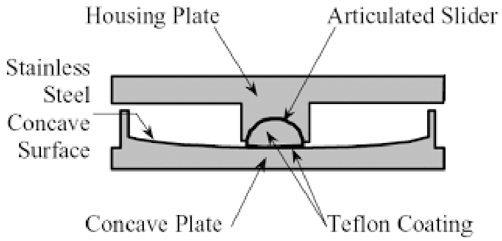


Figure 6. Friction pendulum system section

Earthquake isolation unit preliminary design

While making the preliminary design of the Curved Surface Friction Insulation Unit, the values of λ top = 1.6, λ bottom = 0.8 are included in the calculations since the radius of curvature (R) and dynamic friction coefficient (μ) are the design criteria of each manufacturer. Lower limit values for DD-1 earthquake, the upper limit value is used for DD-2.

μ=0.005; and R= 3000 mm is taken.

For the dynamic friction coefficient DD1 earthquake, λ low should be calculated in the calculation of the curved surface friction base isolation unit. The data from the insulation unit manufacturer and the lower and upper values of λ may take different values. In Table 1, the limit values table found in TBDY 2018 is given.

Table 1. TBDY 2018 limit values

λ	Low	Top
λ_{ae}	1	1.20
λ_{test}	0.70	1.30
λ_{spec}	0.85	1.15

$\lambda_{top} = [1 + 0.75(\lambda_{ae,\ top} - 1)]\ \lambda_{test,\ top}\ \lambda_{spec,\ top}$

$\lambda_{alt} = [1 - 0.75(1 - \lambda_{ae,\ lower})]\ \lambda_{test,\ lower}\ \lambda_{spec,lower}$

In this study, λ_{top} = 1.6, λ_{bottom} = 0.8 values are included in the calculations.

For the design according to the equivalent earthquake load method, the friction coefficient μ=0.005, the insulator radius of curvature R=3.0 m, the target insulator displacement D= 0.185 m in the calculation for the upper limit for the DD-2 earthquake and D=0.674 in the calculation for the lower limit for the DD-1 earthquake. It was found as m as a result of iteration. A design was made for these values, and the target periods were found to be T=2.29 s for the upper limit for the DD-2 earthquake and T=3.44 s for the lower limit for the DD-1 earthquake. The design parameters of the isolator used in the study, used in the ETABS program, are summarized in Table 2. The period values of the built-in support and earthquake-insulated models of the building are given in Table 3.

Table 2. Design parameters

Parameter	FPS
Radius of curvature, Re	3000 mm
Dynamic coefficient of friction, μe	0.05
Seismic weight, W	40738 kN
Effective stiffness (KM)	799.90 kN/m
Effective yield strength (F_y)	81.48 kN
Displacement (DM)	674 mm
Secondary stiffness (k2)	13579.33 kN/m

Table 3. Period values

Period(s)	Fixed support(s)	Base isolation(s)
T_1	0.52	3.44
T_2	0.34	3.37
T_3	0.28	2.99

Selected and scaled earthquake records

Within the scope of the study, a total of 11 sets of acceleration records were selected from the Pacific Earthquake Engineering Research Center Strong Ground Motion Database (Peer, 2019). Both components of these recordings are scaled using the same scale factor for the elastic acceleration spectrum for the 5% elastic damping ratio. Spectral Matching, which is the most recommended earthquake record selection method with seismic codes, was used for scaling (Kayhan et al., 2011).

The most important aspect of using spectrum matching is that it reduces the dispersion between analyzes and enables a realistic estimation of the average response using less ground motion (Karakutuk, 2015). The rules in TBDY-2018 for the selection and scaling of earthquake records of earthquake insulated buildings are given below. (TBDY, 2018)

- Earthquake moment magnitude, earthquake ground motions in the range of MW = 6.2 – 7.51 were selected.
- All design spectra and resultant spectra were obtained for 5% damping.
- The resultant spectrum was obtained by taking the square root of the sum of the squares of the spectra of the two components of the earthquake ground motion.
- Earthquake records will be scaled on the condition that the average amplitudes of all earthquake records selected for one- or two-dimensional calculation between 0.5TM and 1.25TM periods are not smaller than the amplitudes of the design spectrum defined according to TBDY 2.3.4 and 2.4.1 in the same period range. The same scale factor will be used for scaling both horizontal components.

•As specified in TBDY 2018 Section 2.5.3, the selected earthquake records were scaled in the database to ensure Spectral Coherence of Earthquake Records.

Selected 6 earthquakes and their characteristics are given above. These values were compared with the Geometric Mean Hazard Spectrum obtained for the DD-1 earthquake level, which was obtained to show the effects on the earthquake design spectra in the report. According to the rule, the amplitudes of the earthquake ground motion components will be scaled. In accordance with TBDY 2018 Section 2.5.2, the amplitudes between the 0.2Tp and 1.5Tp periods are greater than 1.3. This situation is shown in Figure 7.

Table 4. Selected earthquake ground motions

No.	RSN	Station	Earthquake	Mw	Scale
1	779	LGPC	Loma Prieta	6.93	0.86
2	1084	Sylmar	Northridge-01	6.69	0.71
3	1106	KJMA	Kobe, Japan	6.9	0.72
4	1176	Yarimca	Kocaeli, Turkey	7.51	1.55
5	1614	Lamont 1061	Duzce, Turkey	7.14	4.89
6	3759	W.Trout Far	Landers	7.28	5.40

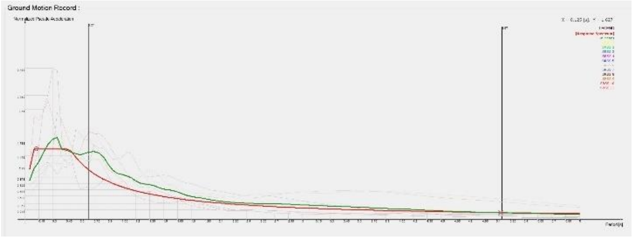


Figure 7. Spectral acceleration resultant spectrums

RESULTS AND DISCUSSION

Evaluation of earthquake behavior

In the analysis model of the building, 6 earthquake records given in Table 4 and earthquakes in the horizontal (X) and (Y) directions perpendicular to each other in the horizontal direction were included in the analysis, while the X and Y directions were included, and 12 earthquake records, 2×6, were selected and added to the analysis system as shown below. Since the nonlinearity in the structure is only in the insulation units, Time History Nonlinear Modal (FNA) was used as the solution method. The earthquake behavior results of both the fixed support and the base isolated structure are given below.

Earthquake isolation unit analysis results

The displacement calculation has been made for the frictional base isolation unit with a curved surface. The maximum displacement under DD-1 loads was found and compared with the preliminary analysis results. The analysis results of the 2×11 earthquakes previously defined for the structure, the displacement average (SRSS-Square Root of the Sum of Squares) was 555.26 mm. It is 0.86 when it is divided by the displacement calculated by the effective earthquake method, which is 674 mm, and its ratio. These results appear in Table 5.28. According to TBDY 14.14.4.6, this value should not be less than 0.8. Since the ratios of the results here were more than 0.8, there was no problem in the displacement results.

Table 5. Base isolation unit displacement results

Base isolation unit displacement results					
Floor	**Link**	**Earthquakes**	**U2**	**U3**	**Average**
			mm	mm	mm
B	K18	R1-1	438	410	600
B	K18	R1-2	333	413	531
B	K18	R2-1	327	380	591
B	K18	R2-2	405	398	568
B	K18	R3-1	555	326	644
B	K18	R3-2	345	525	629
B	K18	R4-1	382	442	584
B	K18	R4-2	471	361	593
B	K18	R5-1	414	349	582
B	K18	R5-2	369	396	542
B	K18	R6-1	393	397	559
B	K18	R6-2	415	381	563
Average					**582**
Average / effective earthquake					**0.86**

Modal analysis results of base isolation and fixed support building

In TBDY 2018 Article 4.8.1.2, every mode where the sufficient number of vibration modes to be taken into account in modal calculation methods is greater than 95% and 3% in both directions of the total mass of the base shear force calculated in both directions should be considered. When we look at the modal analysis for the built-in support building, it is seen that considering the results of the first 48 modes of the earthquake-proof building, it is sufficient to consider the first 6 modes. The period values of the two structures are given below.

Table 6. Period results

Periods		
	Mod	**Period(s)**
Base isolation	1	3.44
	2	3.37
	3	2.99
	4	0.23
	5	0.18
Fixed Support	1	0.52
	2	0.34
	3	0.28
	4	0.15
	5	0.14

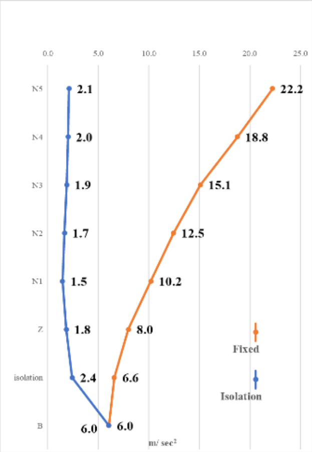
Floor acceleration results of building with fixed support and base isolation support

One of the most important effects of base isolation application is the reducing effects on floor accelerations. In order to compare this feature with the built-in support building, calculations have been made and given in the form of tables and graphics for R1-1 earthquake loading Figure 7.

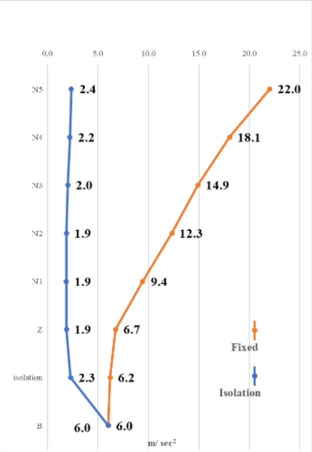
Base shear force results of base isolated and fixed support building

Base isolation causes a significant decrease in the base shear force of the building to which it is applied, and with this reduction, the building is protected from the destructive effects of the earthquake. In order to compare this feature with the built-in support system, the calculations were made and the graph of the base shear force of the base isolation and fixed support building according to the 12 earthquake loadings is given comparatively below in Figures 9-12.

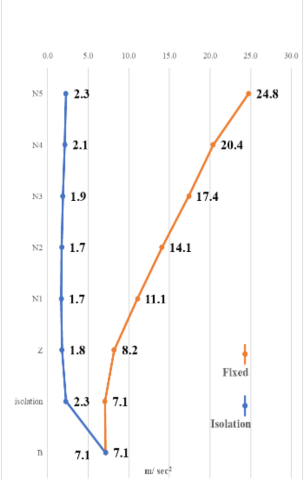
Figure 8. Floor acceleration results



R 1- 1



R 1- 2



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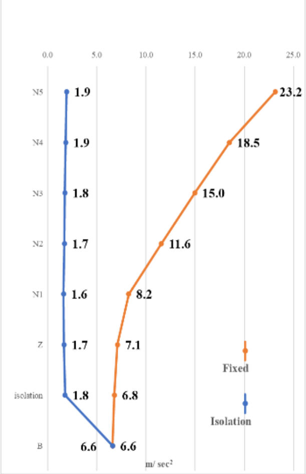
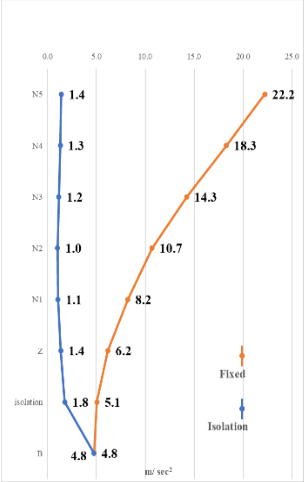
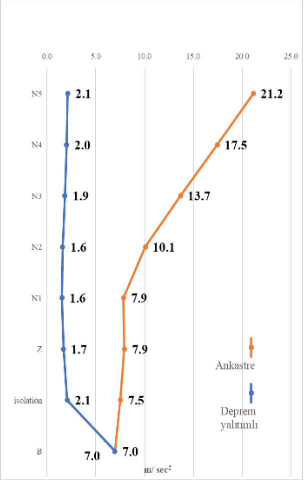


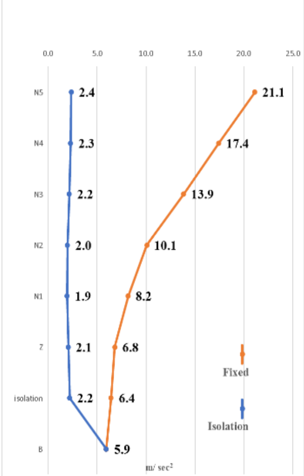
R 1- 3



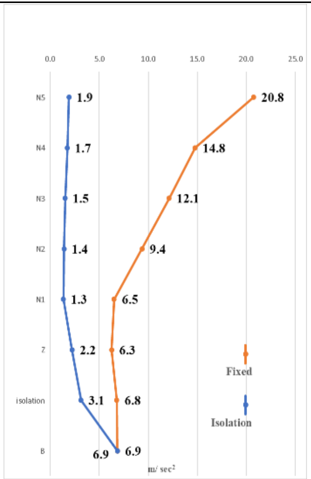
R 1- 4



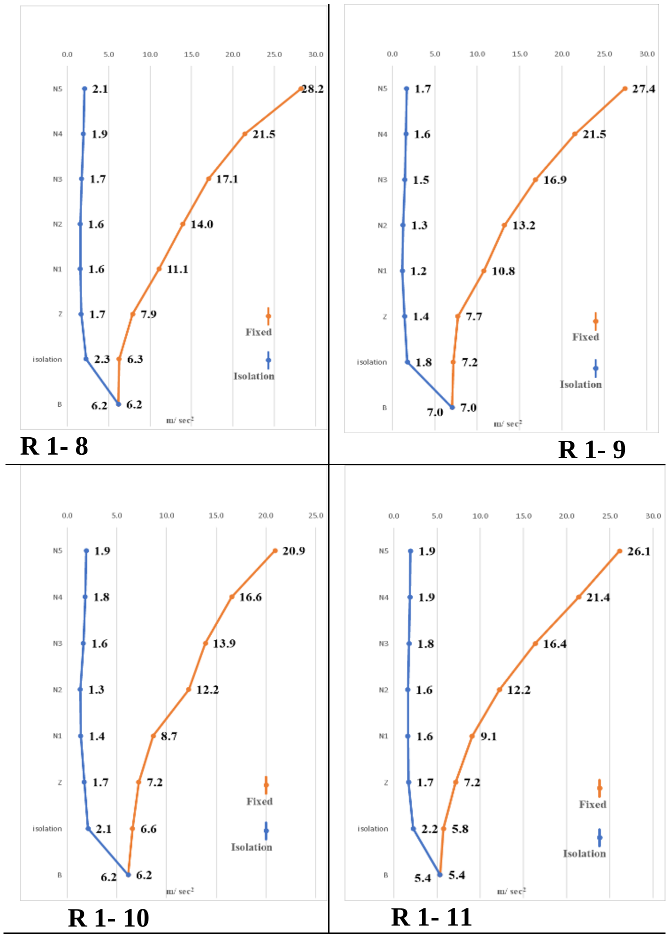
R 1- 5



R 1- 6



R 1- 7



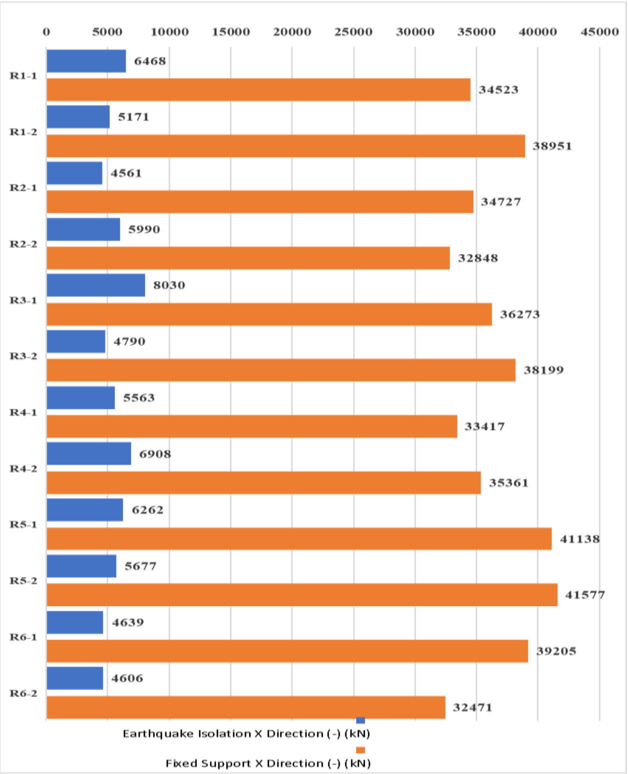


Figure 10. Base shear force results in X (-) direction for 12 earthquake records of an earthquake insulated and built-in support building

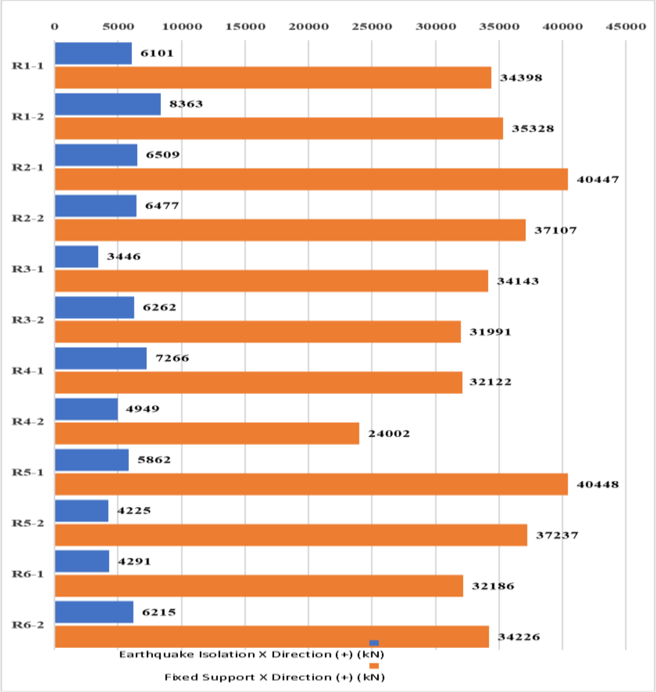


Figure 9. Base shear force results in X (+) direction for 12 earthquake records of an earthquake insulated and built-in support building

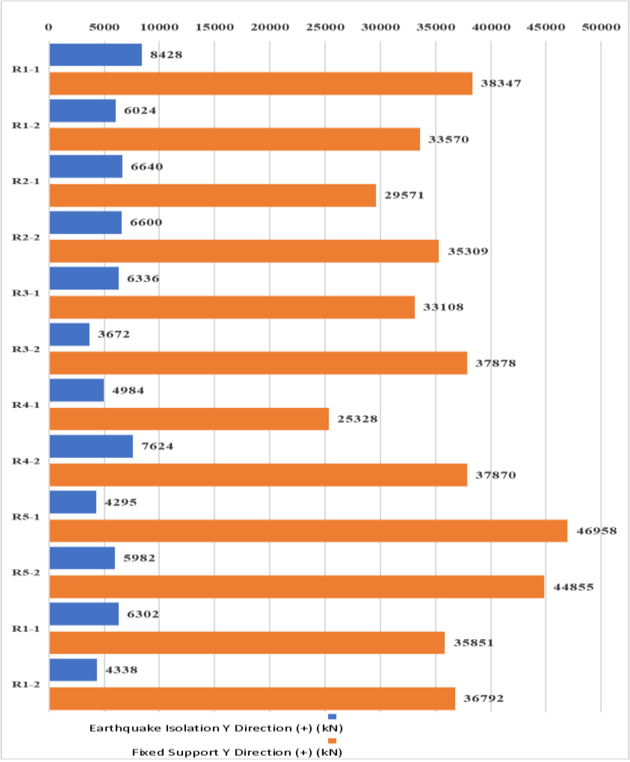


Figure 11. Base shear force results in Y (+) direction for 12 earthquake records of an earthquake insulated and built-in support building

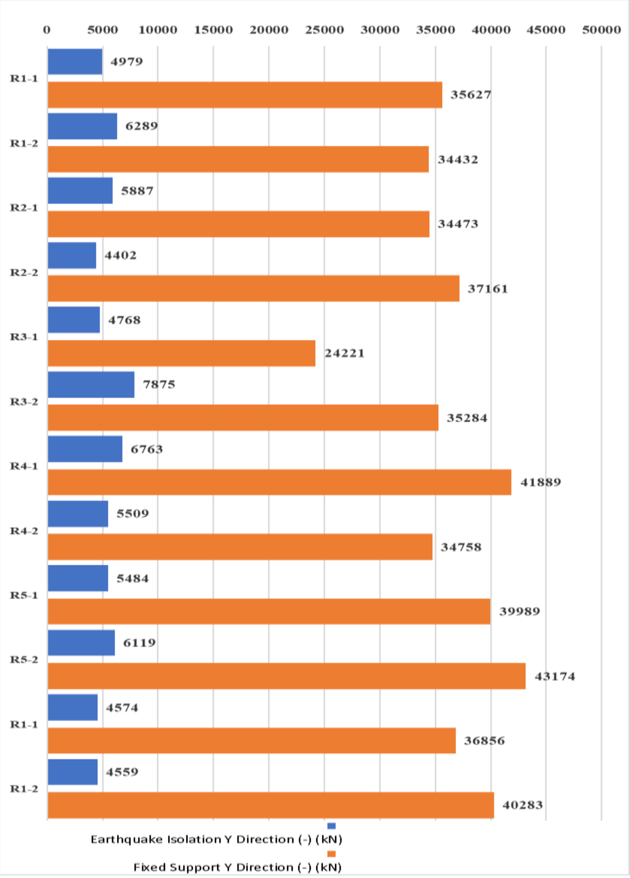


Figure 12. Base shear force results in Y (-) direction for 12 earthquake records of an earthquake insulated and built-in support building

CONCLUSIONS AND RECOMMENDATIONS

In this study, T.R. Turkey Building Earthquake Code 2018 with the ETABS finite element package program, separately as a reinforced concrete frame structure with limited ductility level by changing the earthquake insulated and carrier system of a built-in support and high ductility level non-gap-walled structure constructed by the Mass Housing Administration of the Ministry of Environment, Urbanization and Climate Change. According to, time history analysis was made and findings that enable us to understand the behavior of the structures under earthquakes such as period, base shear force and floor accelerations were obtained for both the fixed support and the earthquake insulated building. According to the findings of the study:

The period of the cantilevered structure in the 1st Mode is 0.515 s, while the period of the earthquake-insulated structure is 3.44 s. With the effect of the increasing period, the acceleration values to the floors decreased.

According to the modal analysis results, the condition of 95% mass participation in the X, Y and Z directions was met in the 48th Mode of the base isolation support structure, while in the 6th Mode with earthquake isolation. In this respect, it has been observed that the use of base isolation has a positive effect on the earthquake behavior of the building.

When we look at the analysis results in terms of floor acceleration results, it is seen that the floor accelerations increase towards the upper floors in the built-in support structure, while the accelerations are maximum at the insulation unit level due to the movement of the insulation units in the earthquake-proof structure, it decreases at the insulation unit level and almost does not change towards the upper floors. As a result, the decreasing floor acceleration contributes to the protection of sensitive non-structural elements from earthquake damage. In addition to the time history results given separately for all earthquake records in the 6th section, it was seen that the average of 22 earthquake records applied to the building was 6.39 m/s^2 for the basement floor and 24.33 m/s^2 for the 5th normal floor. In the earthquake insulated building under the same loads, the average basement floor is 6.18 m/s^2 under the insulation units, and 1.92 m/s^2 for the 5th normal floor. Thus, it is seen that the use of base isolation applied to the building reduces the floor accelerations by approximately 92% on the top floor. It is one of the most basic indicators showing that base isolation protects the building from earthquake damage.

When we look at the results of the analysis in terms of the relative base shear force results; The base shear forces formed by the effect of the incoming earthquake force are 34470 kN in the X(+) direction on average, 5831 kN in the earthquake-insulated building, 36558 kN in the X (-) direction on average, and 5722 kN in the earthquake-insulated building, In the Y(+) direction, it was 36146.07 kN in the built-in support building, 5926.23 kN in the earthquake-proof building, 36286 kN in the Y(-) direction on average, in the built-in support building, and 5935 kN in the earthquake-insulated building. As a result, the base shear force decreased by 83.08 % in the X(+) direction, 84.35 % in the X(-) direction, 83.64 % in the Y(+) direction and 84.66 % in the Y(-) direction in the earthquake isolation applied structure. This clearly demonstrated how base isolation protects the building from the shear force of the base, which causes great damage throughout the building.

As a result of the analyzes made in the time domain according to TBDY 2018, it can be concluded that the base isolation application is an efficient method used to reduce the earthquake forces and to put the structure into service immediately after the earthquake.

On the other hand, base isolation method is used in the strengthening of historical buildings and in residential buildings, which are our living spaces rather than hospital buildings, which are frequently applied in our country. It is indispensable for the country's economy not to be damaged.

DECLARATIONS

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Conflict of interest

The authors hereby confirm that there is no conflict of interest whatsoever with any third party.

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