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The Effects of Using Different Seismic Bearing on the Behavior and Seismic Response of High-Rise Building

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Abstract

The effects of using different seismic bearings were investigated to reduce the seismic response of buildings by assuming the vulnerability of 20-story regular RC building in this paper. The method of this study was that the studied building was studied in three different models in terms of its connection to the foundation. In the first model, the structures were placed on the rigid bearing and in the second and third models; lead-rubber bearings and friction pendulum bearings were placed at the counter between the structure and foundation, respectively. Then, the dynamic analysis was used to assess the behaviour and seismic response of the mentioned models. The results of the study showed that the structures in the first model functioned like cantilever column that would become uniaxial and biaxial bending under the effects of earthquake around the vertical axis of structure. Due to the tensile (tension) weakness in concrete, seismic loads caused major cracks in the tension part of the structures according to the place of the neutral axis that could lead to the collapse of structure. In addition, the use of mentioned seismic bearings under the earthquake caused the structure like a semi-rigid box slid on this equipment that reduced the structure's stiffness and increased the period of the structure in comparison with the first model. Using the studied seismic bearings caused the displacement of the roof of the first and twentieth stories of the structure become approximately equal and prevented the creation of the bending moment in the first model. The results of non-linear time history analysis showed that using the studied seismic bearings caused the response of the structure reduced significantly when the structure was placed on rigid bearings. It could be very valuable regarding the limitation of the capacity of the structure's members.

Keywords: Seismic Retrofit; High-Rise Building; Lead-Rubber Bearings; Friction Pendulum Bearings.

1. Introduction

One of the important issues in the existing buildings is their design in accordance with codes that are developed many years ago and these codes have been revised several times so far. By investigating the behavior of existing buildings against recent earthquakes and assessing the vulnerability of structures (especially in areas that earthquake accrued less during these years), it has been observed that these buildings are vulnerable to the earthquakes.

With the advancement of computers and consequently structural analysis-design softwares, great change happened in the civil engineering sciences that lead to the correction and permanent promotion of the codes. Besides, with the progress and development of seismographs, it was revealed that a significant number of earthquakes (especially earthquakes occurred near fault) had significant acceleration components which were much larger than the normal values stated in the codes (0.35 g - 0.4 g) respectively. The design of structures with high importance against accelerations much greater than the code's values is costly in terms of economic and very space-occupying and improper design. Because of the mentioned causes, using energy dissipation devices in structures due to the significant dissipation of energy caused by earthquake is one of the solutions against acceleration of bedrock in seismic design of structures.

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2. Background Research

Recently, using energy dissipation devices for retrofitting structures against earthquake is common in the academic research. In a comprehensive study, kinds of equipment and methods of increasing dissipating energy in structural systems were investigated. It was shown the use of dampers in the discussed structures has the property that in all cases even in the most severe earthquakes caused a significant reduction in imposed forces on the structure. This phenomenon is valuable due to the limitation of capacity of structure members [1]. In another study on seismic behavior of based-isolated building by seismic isolators, it was found that their periods increased in comparison with the structures with fixed bearing and on the other hand, the values of response of isolated system reduced significantly [2]. The researchers showed that applying dampers and seismic isolators in bridge could reduce the damages caused by lateral forces several times and the correct design of the equipment would guarantee the high performance of the bridge [3]. In another research, applying friction pendulum bearing and lead-rubber bearings could reduce the base shear of a building significantly compared with when the building bearing was rigid [4].

In a case study, the results of the study indicated that the use of friction pendulum bearings could reduce the seismic response of the structure significantly compared to the case where the bearing of structures was rigid [5]. In a detailed study, it was found that by increasing the radius concavity of the foundation, the impact of reflecting mechanism of structure under its own weight, especially at 5-storey models, was reduced and possibly the structure did not return to its original location after occurring earthquake. The best way to solve this problem was the use of displacement limiter or mechanism that returned the structure to its original place after the earthquake. The nonlinear response of displacement and base shear in the modeled 2-story building and 5-story building equipped with common friction pendulum isolators (first model) and isolation system with pendulum movement mechanism for whole structure (second model) showed the reduction in the values of base shear structure in the second model in comparison with the first model [6]. In another detailed study, the seismic behavior of multiple-span RC bridges was evaluated at the different states of using the lead-rubber bearings, friction pendulum bearing at the counter between the deck with cab beam and abutments. It was found that the mentioned operation could reduce the seismic response of structures significantly in comparison with the rigid connection state of deck to cab beam and abutments [7]. Some researchers found that the seismic response of the RC short building could be reduced by using of seismic bearings [8]. The researchers showed that linear analysis is not recommended for the analysis of the isolated structures [9].

Despite extensive studies, a worthy research has not done about the seismic retrofitting of RC high-rise building using lead rubber bearing and friction pendulum bearing so far. Therefore, the seismic response of RC high-rise building has been investigated using seismic bearing in this study. The method of study is that the studied building at the first state with the fixed support has been introduced as the first model. In the second and third models, the states are investigated in order that lead rubber bearing and friction pendulum bearing are used at the counter between foundation and structure. These three models have been studied by the non-linear time-history analysis and Eigen vector analysis.

3. The Studied Equipment

3.1. Lead Rubber Bearing

This bearing consists of a lead core that is enclosed in a relatively thick rubber band. The Rubber isolators are not able to provide high damping and energy absorption. The combination of lead core with rubber bands not only provides primary stiffness of structure but also resist isolated structures against lateral loads such as wind or earthquake.

Figure 1. Lead-rubber bearings with different dimension

The reason of selecting the lead for this isolator is its crystal structure. This kind of structure changes by displacement but immediately returns to the original state and thus consecutive yielding under lateral vibrated dynamic loads does not cause to the fatigue phenomenon. The rubber section of this equipment is like rubber isolators with steel plate and has the function of providing reflecting force to the starting point after the end of structure’s vibration [10]. The lead rubber bearings are modeled by SAP2000 software with following characteristics [4]:

Element = Rubber isolator
U1 → Linear effective stiffness= 1500000 KN/M
U2=U3 → Linear effective stiffness= 800 KN/M , U2=U3 → Nonlinear stiffness=2500 KN/M
U2=U3 → Yield strength= 80 , U2=U3 → Post yield stiffness ratio= 0.1

3.2. Friction Pendulum Bearing

This bearing contains a concave surface at the bottom part and a steel flat surface at the top part and a globe with high resistance and low friction at the middle part. Due to the exerting considerable lateral force, the top section of the structure moves on this bearing. The curvature radius of the bottom part of this bearing specifies period of the isolation system. The reflecting force in this bearing is provided by gravity and the weight of the structure. The following figure shows a view of the bearings.

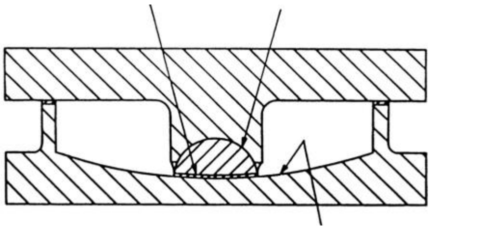

Figure 2. A view of friction pendulum bearing [11]

Friction pendulum bearings with three-dimensional behavior are modeled in SAP2000 software using the following characteristics [4]:
Element= Friction isolator
U1 → Linear effective stiffness= 15000000 KN/M , U1→Nonlinear effective stiffness= 15000000 KN/M
U2=U3 → Linear effective stiffness= 750 KN/M , U2=U3 → Nonlinear stiffness=15000 KN/M
U2=U3 → Friction coefficient slow= 0.03 , U2=U3 → Friction coefficient fast= 0.05
U2=U3 → Rate parameter= 40 , U2=U3 → Radius of sliding surface= 2.23

4. The Studied Building

In this study, a 20-story reinforced concrete building is investigated in which the connections of beams and columns are rigid. The dimensions of the considered structure on each side are 12 m (square plan) and there are four rows of columns in each side at equal distance of 4 m. The used sections and models of structure are based on the following forms:

Table 1. The dimensions of the studied building based on the centimeter

Floor	Dimension	
	Column	Beam
1, 2, 3	70×70	25×60
4, 5, 6	65×65	25×60
7, 8, 9	60×60	25×60
10, 11, 12	55×55	25×60
13, 14, 15	50×50	25×60
16, 17, 18	45×45	25×60
19, 20	40×40	25×60

Figure 3. shows the view of the studied model in the SAP2000 software.

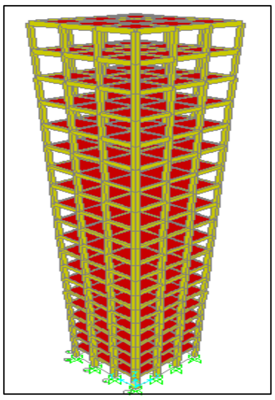

Figure 3. The view of the studied model in the SAP2000 software

According to Figure 4, Mander model is used in order to model the nonlinear behaviour of materials.

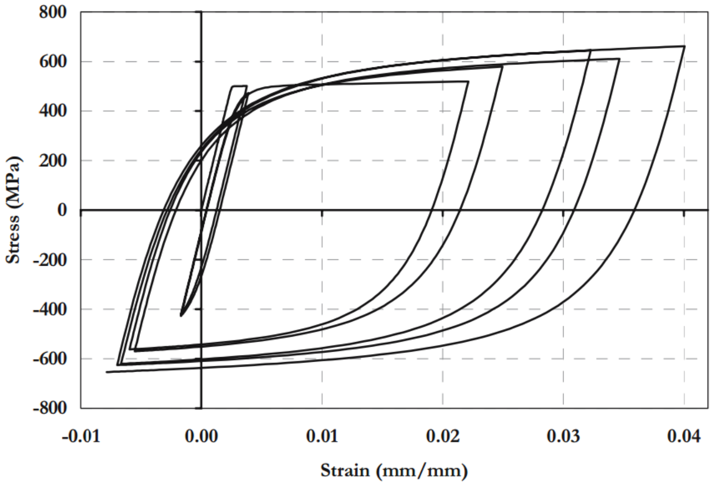

Figure 4-a. Nonlinear behaviour model of steel

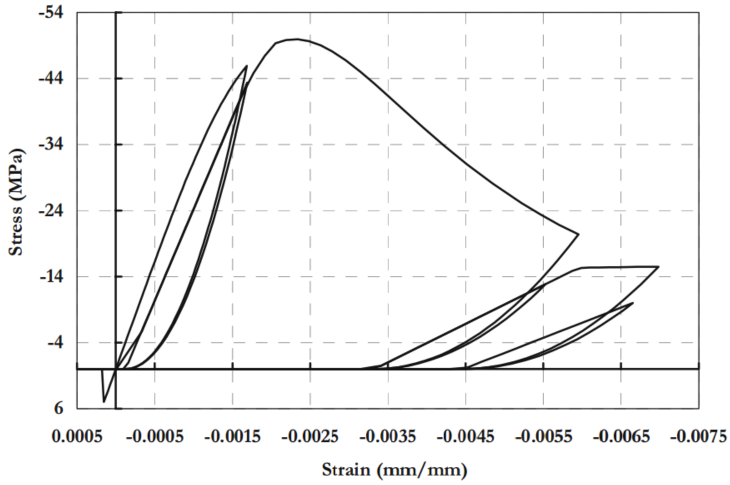

Figure 4-b. Nonlinear behaviour model of concrete

Figure 4. behaviour's models of material [12]

Figures 5 and 6. show a view of how to use seismic bearings in the second and third models.

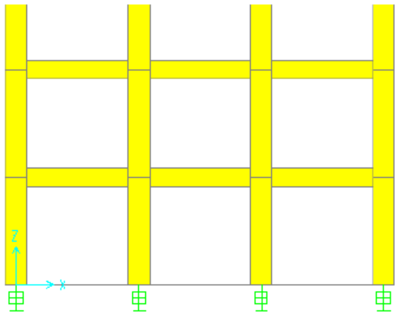

Figure 5. The view of using the lead rubber bearings in the second model

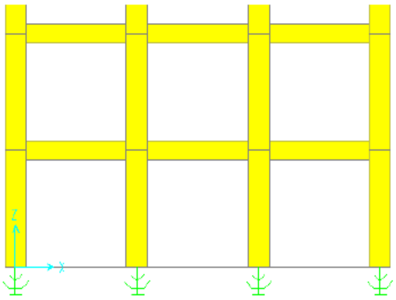

Figure 6. The view of using the friction pendulum bearings in the third model

5. The Features of Selected Earthquakes

In this study, the horizontal components of selective accelerogram elated to the Landers, Loma Prieta, Manjil, Tabas, New Zealand, Northridge and Park Field earthquakes are combined by using SRSS method in order to obtain one spectrum of each earthquake. Then, the Average of the spectra of the seven mentioned earthquakes is obtained and is scaled with 1.3AB spectrum (acceleration spectrum of 2800 standard [13]) within the period of 0.2 T and 1.5 T. Specifications of the earthquakes are presented in the following table.

Table 2. The specifications of the selected earthquakes

Accelerogram	Station
Landers 1992 LCN 260, 345	SCE 24 Lucerne
Loma Prieta WVC 000, 270	CDMG 58235 Saratoga- W vally Coll
Manjil, Iran 1990-06-20-L,T	BHRC 99999 Abbar
New Zealand A-MAT 0.83-353	99999 Matahina Dam
Northridge-01 1994 ORR 090,360	CDMG 24278 Castaic- OLD Ridge Route
Park Field TMB	CDMG 1438 Temblor Pre- 1969
Tabas DAY- LN,TR	9102 Dayhook

6. Eigen Vectors Analysis

Free vibration is the vibration free from any dynamic excitation (such as applying external dynamic forces or the motion of structure base) that begins by disturbing the balance state of the structure by applying the deformation and or the initial speed. The natural vibration (frequency and period) depend only on the mass and rigidity of the structure. The period of natural vibration has an inverse relationship with the natural vibration frequency. N determines the root of characteristic equation ($det[k - \omega_n^2 m] = 0$), the natural frequency, and the natural period of frequency. The roots of mentioned equation are known as Eigen Value (characteristic values or normal values). There is an independent vector φ_n for each of the N natural frequency of a system with N freedom degrees that represents mode vibration shape and is called "The vector of vibration natural mode" or "The shape of vibration natural mode". As a result, there are N vectors of φ_n for an N-degree freedom system that is called eigen vector. The number of selective modes for eigen vector analysis is considered so that the minimum modal mass participation factors reaches to the minimum of the value mentioned in 2800 code (90%). The periods of the first mode of vibration at x and y (horizontal directions) is as follows:

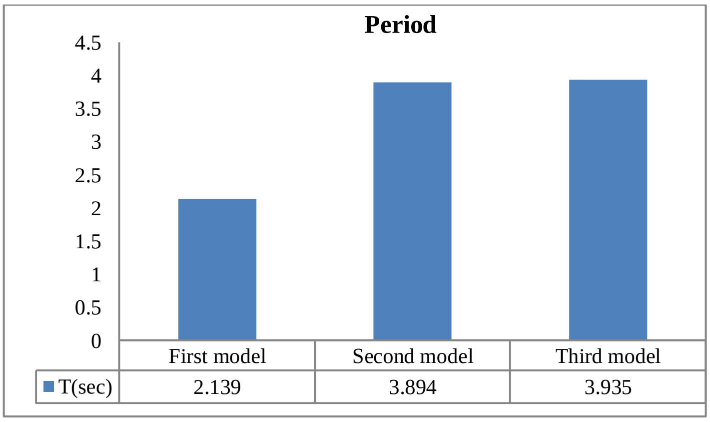

Figure 7. The periods' values of different models of structure

Based on Figure 7, it is shown that the use of mentioned equipment cause to reduce the structure's stiffness and increase its period. The period of structure increases from 2.139 seconds in the first model where the structure is fixed on bearing and to 3.894, 3.935 seconds in the second, third and fourth models by using lead rubber bearing and friction pendulum bearing, respectively.

7. The Non-Linear Time History Analysis and Presenting the Results

The non-linear time history analysis by modal method was done with the zero initial conditions and the definition of the Ritz vectors and specifications of Tabas earthquake with the scale factor of 1.7g. The main model was turned to the three models in order to study the effects of the studied energy dissipation device. The first model was the connection of the structure to the foundation that was rigid and in the second, third, and fourth models at three distinct models, lead-rubber bearing and friction pendulum bearing at the interface between structure and foundation was s used respectively. It should be noted that united system of all figures was ton-m.

Graphs of the displacement of the different point's structure at the longitudinal and transverse directions with respect to time:

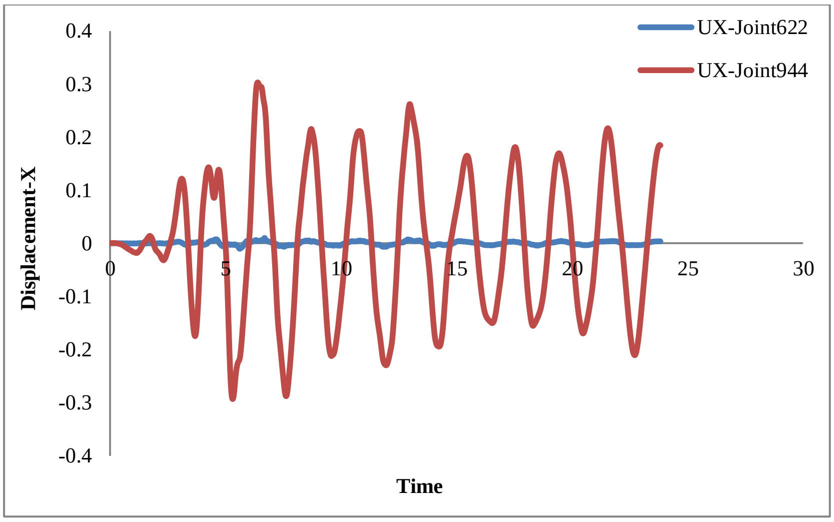

Figure 8-a. Displacement-X direction

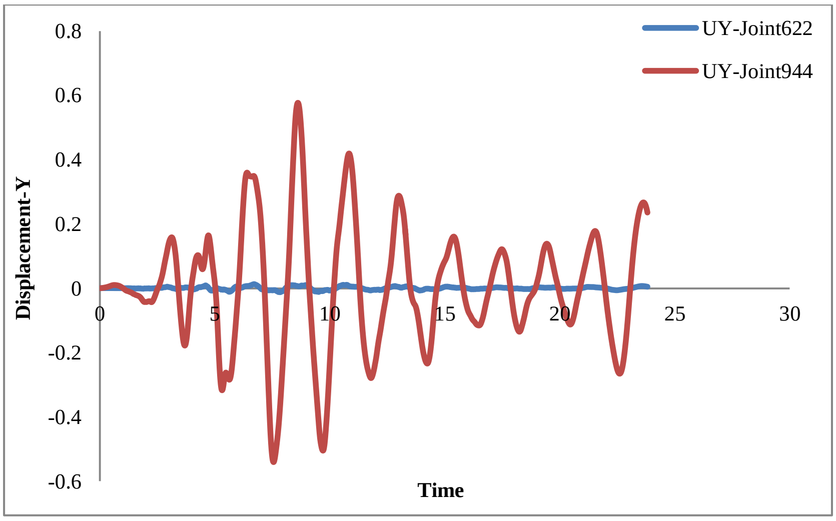

Figure 8-b. Displacement- Y direction

Figure 8. The horizontal displacement of different points of the first model at x direction and y direction

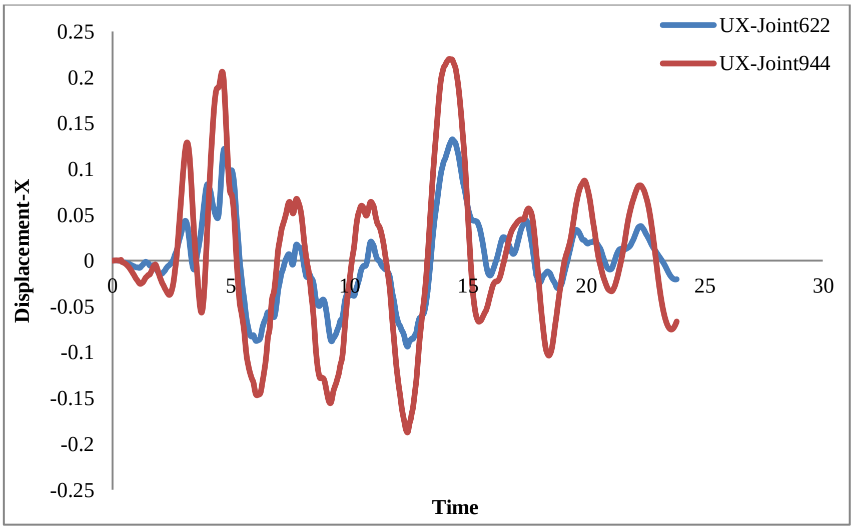

Figure 9-a. Displacement-X direction

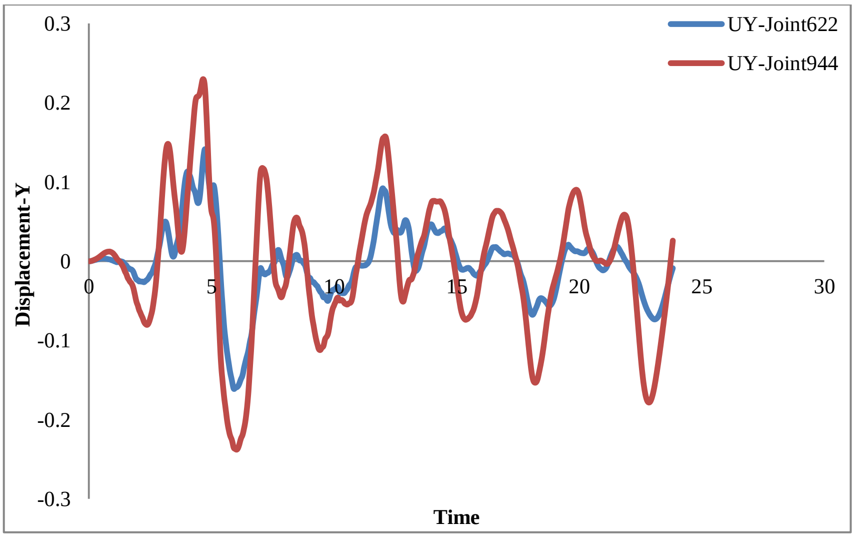

Figure 9-b. Displacement-Y direction

Figure 9. The horizontal displacement of different points of the second model at x direction and y direction

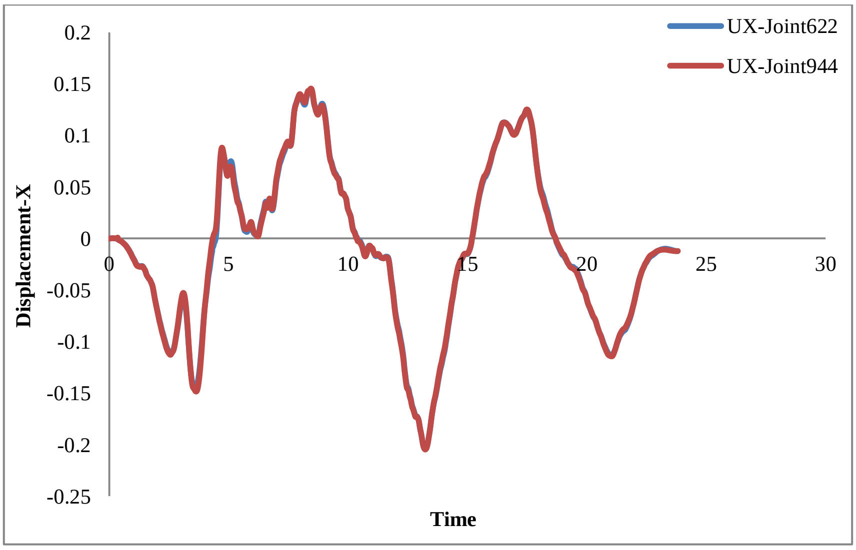

Figure 10-a. Displacement-X direction

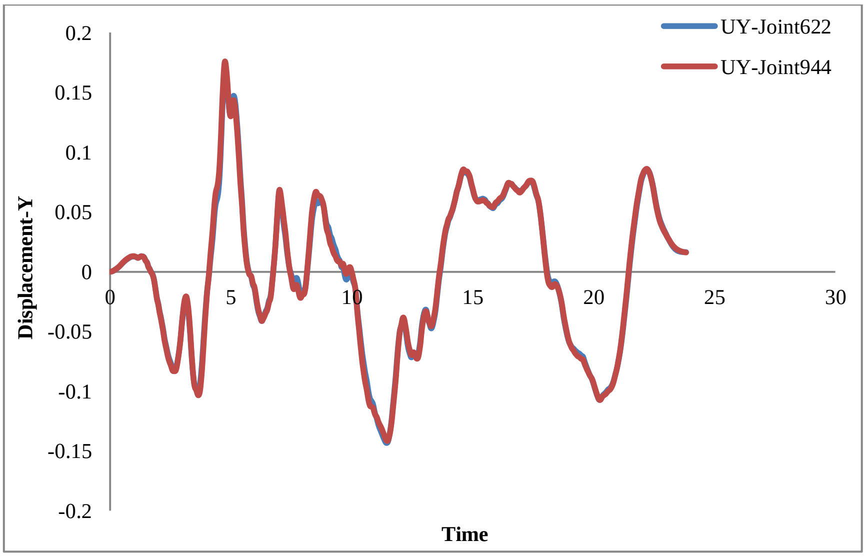

Figure 10-b. Displacement-Y direction

Figure 10. The horizontal displacement of different points of the third model at x direction and y direction

Based on the Figure 8, the rigid connection of structure to the foundation causes that the lower stories of structures closer to foundation affected by an earthquake have a very trivial horizontal shift about zero. Due to the openness of the roof of the twentieth story without any constraint, and of course the considerable height of the structure, the considered building acts somewhat similar to a cantilever column, so that the displacement of the considered point (point 622) on the roof the first story at horizontal direction is almost equal to zero and the maximum horizontal displacement of the roof of twentieth story (point 944) at X and Y directions is equal to 30 and 57 cm respectively.

The mentioned points show this fact that the studied building affected by lateral forces such as an earthquake on the lower story are almost fixed and on the upper story becomes bend and causes to create the substantial bending moment in bearing and increases the seismic response of structure. Nonetheless, the existence lead-rubber bearing and friction pendulum bearing between structure and foundation make the structure slides on the equipment under the effect of the earthquake and behave like rigid box on seismic bearing. Therefore, based on the Figures 9 and 10, the displacement of specified point on the floor of first story with the displacement of similar point on twentieth story is almost equal at the both X and Y directions.

The maximum displacement of roof on the twentieth story at X and Y directions is equal to 22 cm and 22 cm for second model and for third model 20 and 17, respectively. The following figure shows a view of schematic two-dimension of structure behavior in different states:

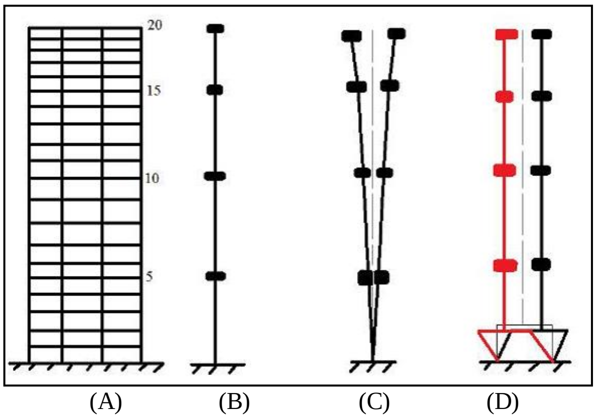

Figure 11. The dynamic model of the studied structure

Figure 11. (A) shows the studied building and the Figure 11. (B) shows a simplified dynamic model. Forms Figure 11. (C) and (D) show the behaviour of structures against lateral loads (e.g. earthquake's load) in rigid connection states of structure to the foundation and the use of seismic bearings between structure and foundation. Considering the deformation of the three-dimensional forms of studied structure in a rigid connection state of the building to the foundation, it is determined that the structure became under uniaxial and biaxial bending in the cross-section of its plan. Considering neutral fibre in any mode of deformation, almost the half of the structure was under tension and the other half was under pressure.

Due to the general weakness of concrete against tension, in the case of non-application of the necessary arrangements for strengthening of structure against the bending phenomenon, the possibility of severe seismic damage and creation of diagonal and tension cracks would increase, which eventually can lead to the destruction or non-usable of structure.

The figures of base shear of longitudinal and transversal directions of different models with the respect to the time:

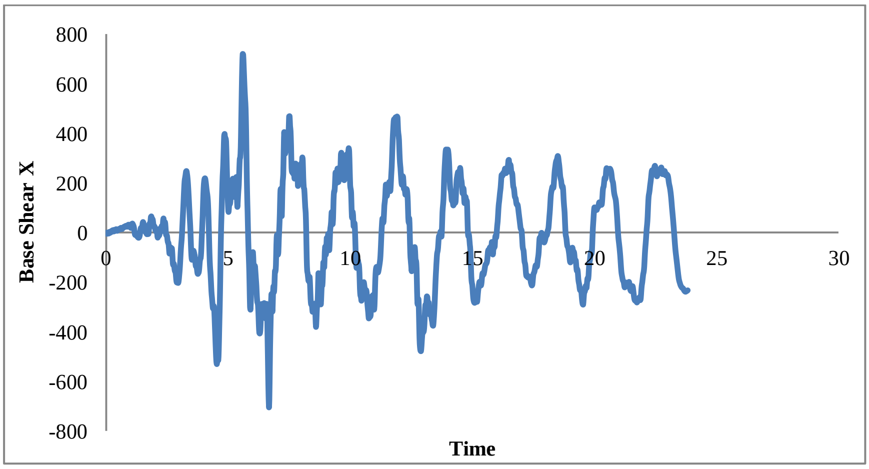

Figure 12-a. Base shear X

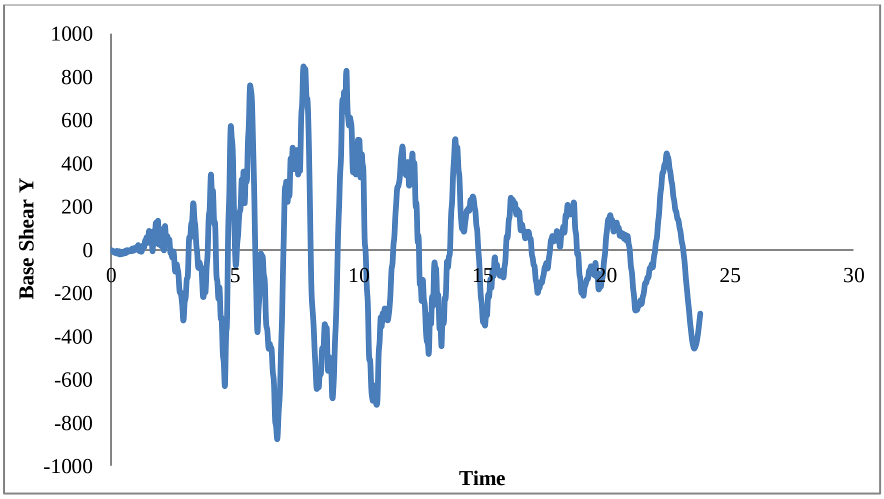

Figure 12-b. Base shear Y

Figure 12. The figures of base shear of structure at horizontal directions of first model

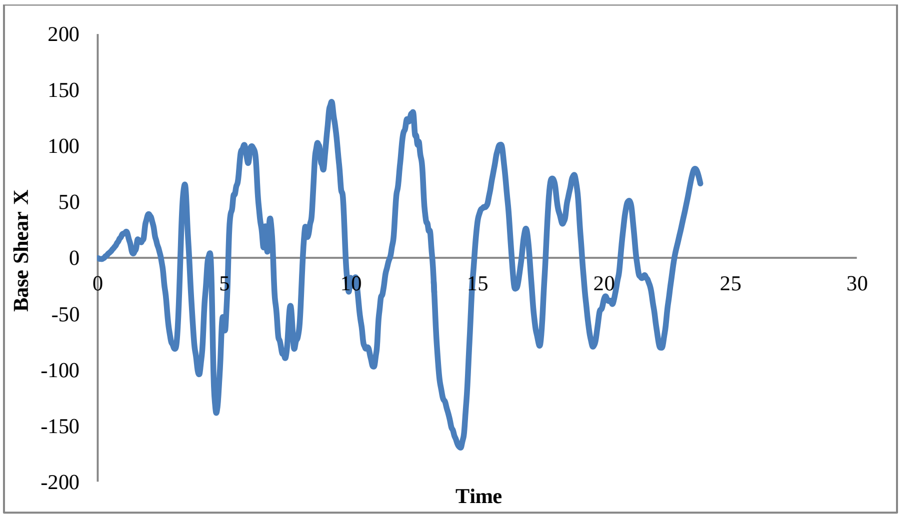

Figure 13-a. Base shear X

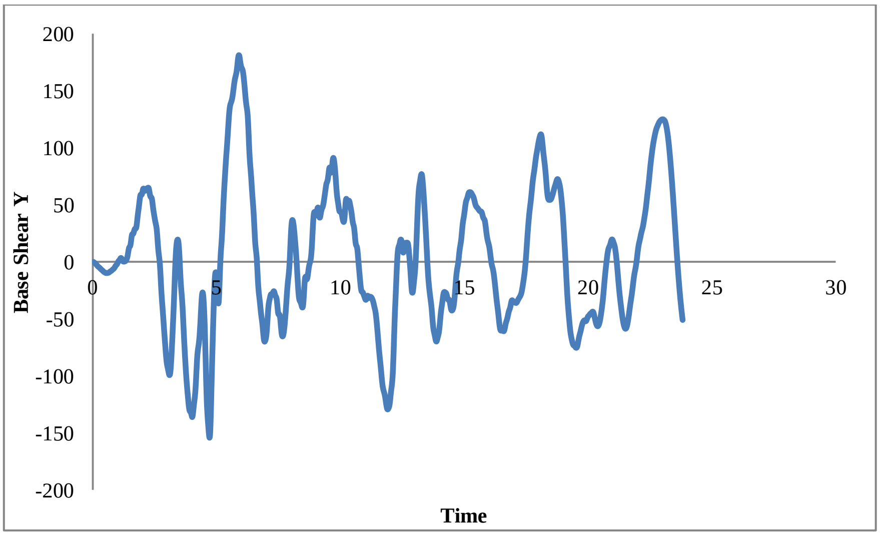

Figure 13-b. Base shear Y

Figure 13. The figures of base shear of structure at horizontal directions of second model

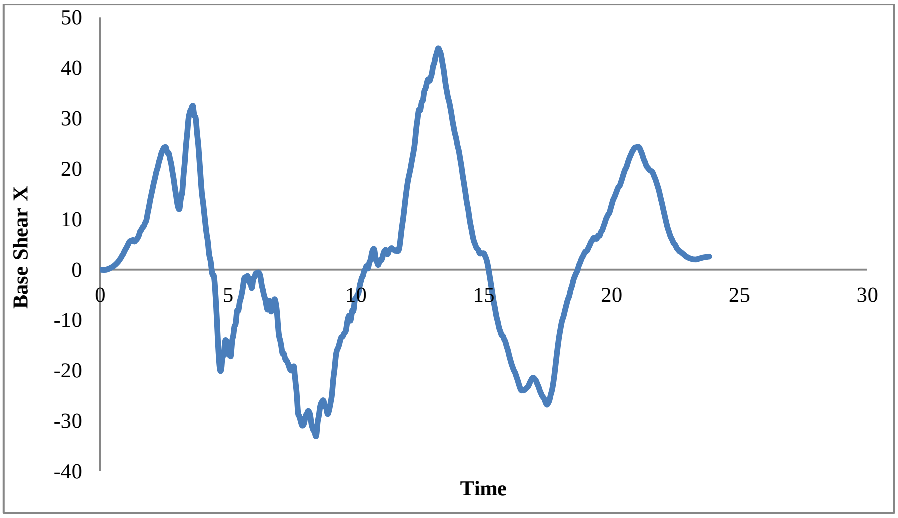

Figure 14-a. Base shear X

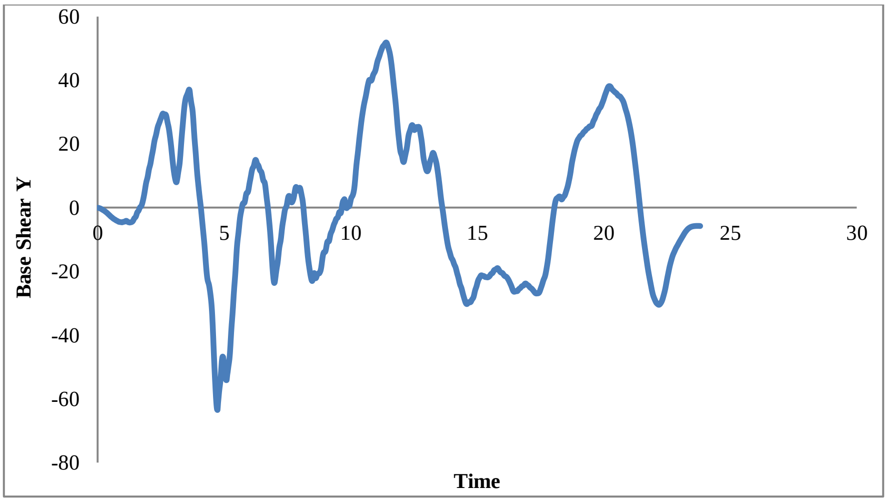

Figure 14-b. Base shear Y

Figure 14. The figures of base shear of structure at horizontal directions of third model

By investigating the results of non-linear time history analysis as shown in Figures 12 to 14, it is obvious that utilizing the studied seismic bearings could reduce the base shear force in comparison with the rigid connection of structure to the foundation, So that the base shear force of the studied building in rigid connection state to foundation at the X and Y directions are 720.1 and 876 tons respectively and these values are reduced to 169.4 and 181.3 tons in use of lead rubber bearings, 43.89 and 63.41 tons in the use of the friction pendulum bearings.

8. Conclusion

The use of the studied seismic bearings could reduce structure's stiffness and subsequently increase its period in comparison with the rigid connection of the structure to the foundation. The period of structure increases from 2.139 seconds in the first model that structure is fixed on bearing and for the second and third models (using lead rubber bearing and friction pendulum bearing) 3.894, 3.935 seconds, respectively.

The base shear force of the studied building in rigid connection state to foundation at the X and Y directions were 720.1 and 876 tons respectively and these values were reduced to 169.4 and 181.3 tons in use of lead rubber bearings, 43.89 and 63.41 tons in the use of the friction pendulum bearings.

In comparison with the first model, using the seismic bearing in second and third models reduces the stiffness of the studied structures and increases its period. Using this equipment has improved the seismic behaviour of the studied structures so that the difference of lateral displacement between the first and the last roofs of the structure has minimized in the case of using this equipment compared to the initial state (first model). This seismic behaviour leads to significant reduction of base shear of the structure in the second and third model than the first model. This result indicates that using lead-rubber bearings and friction pendulum bearings lead to the seismic retrofitting of the studied structure than its initial state.

The results of the study showed that using the studied seismic bearings caused the response of the structure reduced significantly when the structure was placed on rigid bearings. It could be very valuable regarding the limitation of the capacity of the structure's members.

The use of the studied seismic bearings caused that the structure slid on this equipment that finally lead to the dissipation of the transmitted inertia forces to the foundation in comparison with rigid connection state of structure to the foundation. This function prevented the possible seismic damage at the interface between the structure and foundation and also falling equipment and devices inside the building (such as a closet, refrigerator and pictures). Falling of equipment in the building was a common cause of life and property damage at the time of earthquake that this equipment could be handled with bolts or other suitable connectors to structure, of course.

Computer modelling and theoretical design of these bearings for suitable application of them was necessary for reducing the seismic response of structures, however, not sufficient. The use of the mentioned equipment in the different structures enquires urgent need of computer modelling in the finite element method and theoretical design and experimental results requires much experience, talent, and genius designer particularly in the utilizing of them in the existing structure retrofitting.

In the case of existing structures such as buildings and bridges the different kinds of energy dissipation devices could be used in these places by cutting and separating of the different parts of the structure. According to the results of this study, the mentioned function could lead to a considerable reduction of seismic responses in the structure. Doing this action needs high force of plan’s implementers, since it is necessary the upper part of the structure could be controlled by providing special arrangements such as jacking below the structure so that the considered seismic bearings could be put in this place.

Due to the behaviour of the studied energy dissipation devices that are inherently nonlinear in this research, their effects could not be evaluated properly using linear analysis. By proper designing and optimal use of seismic bearing, the seismic response of structure could be reduced significantly in comparison with the rigid connection state of structure to the foundation and the dimensions of structure could be designed in small and optimal dimension that could compensate for the cost of using of the equipment slightly.

Generally, the isolation function of different parts of structure from each other or different parts of structure from foundation and placing seismic bearings in these places could lead to the improvement of structure's behavior and dissipating of imposed seismic forces. Therefore, the selection of appropriate seismic bearing is essential and considerable that could be different in any case study based on the type of structure, place of its use and the condition of the site, ground movement.

Feasibility study of structure instability equipped with seismic bearings is essential due to the various reasons including extreme movements of ground, the weakness of properties in the mentioned equipment affected by various reasons.

It is necessary that some restraints should be created in different parts of the structures in order to prevent the excessive shift of the whole or some parts of the structure that were on the seismic bearings and the instability of the structure due to the excessive displacement.

In addition to the essential requirement for designing of the horizontal restraints, creating restraints against the impact of strike like the vertical component of earthquake, especially in the areas near to the fault for structures equipped with seismic bearing is of a particular importance.

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