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Seismic Isolation vs. Conventional Construction

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Abstract

Based on the huge experience accumulated in Armenia in the field of seismic isolation due to the scientific, engineering and design works of the author of this paper the advantages of seismic isolation vs. conventional construction are clearly stated. New data on the number of seismic isolated newly constructed and retrofitted buildings, as well as of the seismic isolation laminated rubber-steel bearings (SILRSBs) manufactured in Armenia are given. Structural concepts of the considered base isolated buildings are briefly described. Comparison of the deformed states of buildings with and without seismic isolation systems is shown based on the carried out non-linear earthquake response analyses. Also, corresponding values of vibrations' periods, of stories' drifts, and horizontal shear forces at the level of foundation for both cases are presented and compared. Analyses were carried out based on the requirements of the Armenian Seismic Code and also based on acceleration time histories of different earthquakes. It is concluded that for soil conditions of Armenia where during the earthquakes mainly the high frequencies of soils' vibrations are prevailing, there is no alternative to buildings and structures with seismic isolation systems. The cost of construction of new base isolated buildings is less by 30-40% in comparison with the cost of conventionally constructed buildings and the cost of retrofitting of existing buildings by base or roof isolation is from 3 to 5 times less in comparison with the cost of conventionally retrofitted buildings. Therefore, Armenia is the world leader in development and extensive application of low-cost seismic isolation for construction of new and retrofitting of existing buildings. Despite the obvious advantages of seismic (base and roof) isolated buildings the author on his own continuous his permanent struggle against some corrupt governmental bodies and companies which are trying to cause barriers against further development and larger application of seismic isolation systems. It is stressed in the paper that being corrupt they want to apply in construction industry of Armenia only the old conventional methods as they bring to implementation of very expensive (but not resilient) buildings. This leads to a significant waste of public financial resources, but as a result, the reliability of such buildings is significantly inferior to the reliability of seismic isolated buildings where people feel earthquakes from 8 to 10 times less.

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I. Introduction

World experience in application of seismic isolation systems and consequences of strong earthquakes are point out on the high efficiency and advantages of seismic isolated buildings in comparison with the conventionally constructed buildings. In many countries like Japan, Chile, China, Italy, and others application of seismic isolation in construction of civil buildings and critical facilities (schools, hospitals) became actually obligatory. Alas, from this point of view Armenia is not yet in the same line with these countries despite the fact that due to the works of the author of this paper Armenia is the second in the world after Japan by the number of seismic isolated newly constructed or retrofitted buildings per capita (Fig. 1, 2). This statement is confirmed in [1]: "*It is worthwhile stressing that Armenia remains second, at worldwide level, and has the largest number of building applications of seismic isolation per number of residents, in spite of the fact that it is still a developing country*".

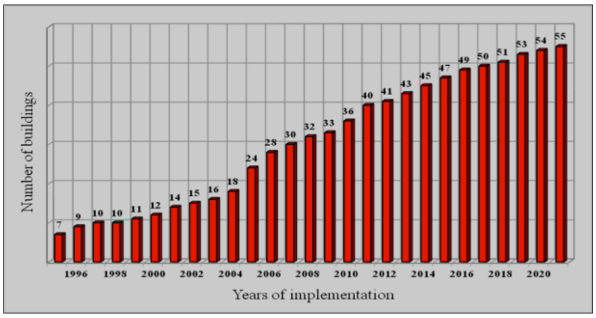

Figure 1. Number of seismic (base and roof) isolated buildings newly constructed or retrofitted in Armenia by years

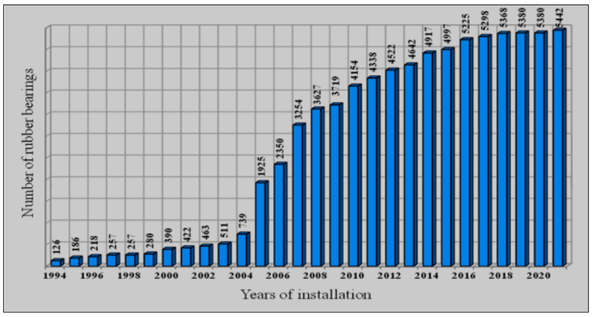

Figure 2. Number of rubber bearings installed in the newly constructed or retrofitted buildings in Armenia by years

Advantages of seismic isolated buildings vs. the conventionally constructed buildings are well stressed in [2]: "*The basic dilemma facing a structural engineer charged with providing superior seismic resistance of a building is how to minimize interstory drift and floor accelerations. Large interstory drifts cause damage to nonstructural components and to equipment that interconnects stories. Interstory drifts can be minimized by stiffening the structure, but this leads to amplification of the ground motion, which leads to high floor accelerations, which can damage sensitive internal equipment. Floor accelerations can be reduced by making the system more flexible, but this leads to large interstory drifts. The only way of reducing simultaneously interstory drifts and floor accelerations is to use base isolation; the isolation provides the necessary flexibility, with the displacements concentrated at the isolation level*".

The above is clearly confirmed and proved by pictures given in Figure 3. These pictures are taken from [3], where it is stated that: *"It is a common opinion that filling in frame structures masonry walls improves the behavior under horizontal loads including seismic actions. This is true only for small loads, and as long as the masonry remains largely intact".*

a
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b
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Figure 3. Examples of poor behavior of conventionally constructed buildings during the 1992 Erzincan earthquake (a) when masonry fell out while the frame remained standing and during the 1999 Izmit earthquake (b) when typical diagonal cracks appeared in reinforced concrete frame masonry infills. Both earthquakes occurred in Turkey

Unfortunately, such a wrong approach using filled in frames in construction of conventional buildings takes place everywhere in Armenia. The reason for that is the above mentioned corruption. It seems that people have completely forgotten the lessons of the terrible and tragic Spitak earthquake of December 7, 1988. They live only for today, thinking about how to get more money, and the best way for them is to build buildings by old unreliable, but very expensive methods, which bring them great profits. These people are no longer interested in what will happen to such buildings in case of strong earthquakes. However, regarding such cases it is explained in [3]: "*The combination of two very different and incompatible construction types performs poorly during earthquakes. The frame structure is relatively flexible and somewhat ductile, while unreinforced masonry is very stiff and fragile and may "explode" under the effect of only small deformations. At the beginning of an earthquake the masonry carries most of the earthquake actions but as the shaking intensifies the masonry fails due to shear or sliding. The appearance of diagonal cracks is characteristic of a seismic failure".* The fairness of this statement is proved by the values of maximum allowable inter-story drifts given in the Armenian Seismic Code for the frame structures and for unreinforced masonry. An average value of inter-story drifts for different types of the frame structures is equal to h/250 and for masonry – h/520, where "h" is the height of the stories. Consequently, masonry structures can withstand the inter-story drifts, which are smaller 2.1 times than maximum allowable inter-story drifts of the frame structures. This explains why in conventionally constructed buildings damages and destructions happen first in masonry that fills in the frames.

On the contrary to the buildings constructed using the old conventional methods, seismic isolated buildings constructed in different countries have demonstrated highly reliable behavior under the strong seismic impacts. The examples are given in [4] and relate to demonstration of the effectiveness of seismic isolation in the Hanshin-Awaji Earthquake in the northern area of Kobe-city in Japan. There were two base isolated buildings, namely, the computer center of the Ministry of Posts and Telecommunications (Fig. 4) and the laboratory building of a construction company (Fig. 5).

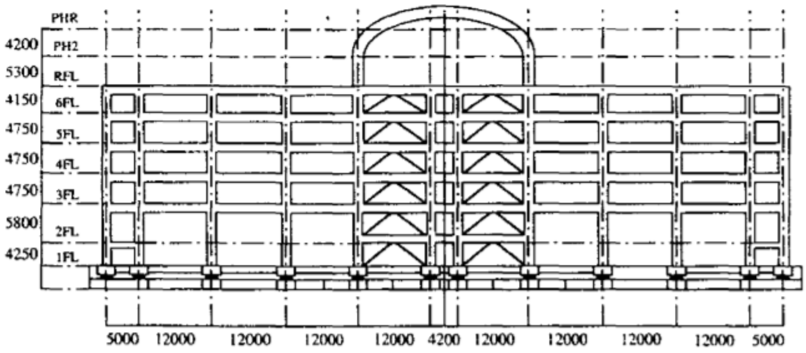


Figure 4. Vertical structural elevation of the base isolated computer center building in Kobe

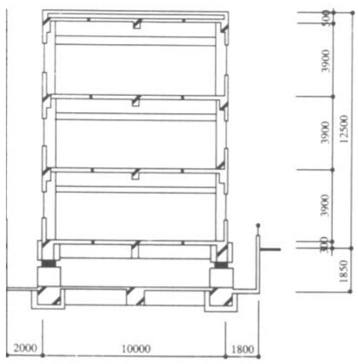


Figure 5. Vertical structural elevation of the base isolated laboratory building in Kobe

In both cases the good performance was demonstrated and in [4] it is stated: "*The isolation performance of the base isolated computer center was excellent and of the laboratory building was satisfactory. ...The success of the base isolated buildings in the Hanshin-Awaji earthquake convinced structural engineers and architects of effectiveness of seismic isolation. Since the earthquake, construction of base isolated buildings has explosively progressed*".

II. Comparison of the Limit Deformed States, Inter-Story Drifts and other Parameters of Various Buildings with and without Seismic Isolation Systems

2.1 Structural Concept of the 18-Story Base Isolated Building "Northern Ray"

The project on analysis and design of the 18-story base isolated buildings twins of the multifunctional residential complex "Northern Ray" was accomplished in 2007 [5]. Construction of this complex in Yerevan was completed by the end of 2010 (Fig. 6). The considered building has one parking floor below the isolation plane and two parking floors above the isolation plane designed using R/C strong and rigid structural elements. The cross sections of columns vary from 700×700 mm, 700×1000 mm to 700×1900 mm, and those of beams – from 700×600(h) mm to 700×650(h) mm. The thickness of shear walls is equal to 300-400 mm. The cross section of the foundation strips is 1000×1200(h) mm. Both the elevators' shafts and staircases in the building were also designed as the rigid cores with the thickness of their walls equal to 300 mm.

Figure 6. Architectural design view of the 18-story base isolated buildings of residential complex “Northern Ray” from the Northern side and its current view from the Southern side

The accepted structural solution allowed obtaining a rigid system below the isolation plane and also the substantial rigidity was provided to the superstructure (the part of the building above the isolation plane) consisted of 15 residential floors. This was achieved by using R/C columns with cross section of 500×500 mm and 600×600 mm and shear walls between them with the thickness of 160 mm. Along all exterior axes strong beams were designed with a cross section of 500×650(h) mm and along the interior axes the beams have cross section of 500×350(h) mm. The thickness of R/C slabs was set at 150 mm for all floors. The elevators’ shafts and staircases in superstructure were designed in the same way as for the part of the building below the seismic isolation plane.

The building is designed in an unusual shape. This was dictated by architectural solution. Starting from the level of 17.45 m the building has a cantilever part the span of which increases towards the top of the building (total span at the top is equal to 22.4 m). Such a solution would have brought to significant complications if this building were to be designed with conventional foundations. Actually, nobody in the country agreed to design this building. Only the structural concept suggested by the author of this paper, along with application of base isolation technology, made it possible to design and erect this structure, which is remarkably interesting from the engineering point of view and quite unusual. In the considered building the approach to install clusters of small size rubber bearings was used [6]. Different numbers of rubber bearings are installed under different columns and shear walls. All medium damping rubber bearings (total 904 pieces) are of the same size and characteristics given in [7].

2.2 Results of Analyses for the 18-Story Building “Northern Ray” with and without Seismic Isolation System

Earthquake response analysis of the considered building was carried based on the developed design model shown in Figure 7. Calculations were carried out considering the non-linear behavior of seismic isolation rubber bearings with the following input parameters: yield strength – 56 kN; yield displacement – 19 mm; effective horizontal stiffness – 0.81 kN/mm. For the time history non-linear earthquake response analysis, a group consisting of 9 accelerograms was used, including a synthesized accelerogram [7]. They were chosen in a manner that the predominant periods of the Fourier spectra do not exceed 0.5-0.6 sec. This corresponds to the soil conditions of the construction site. Also, the building was analyzed based on the provisions of the Armenian Seismic Code with consideration of the same input parameters regarding the soil conditions, seismic zone and expected maximum acceleration of 0.4g. Some results of calculations are given in Table 1.

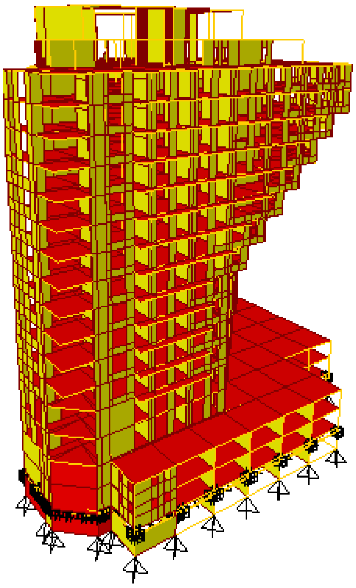


Figure 7. Design model of the 18-story base isolated building of residential complex “Northern Ray”

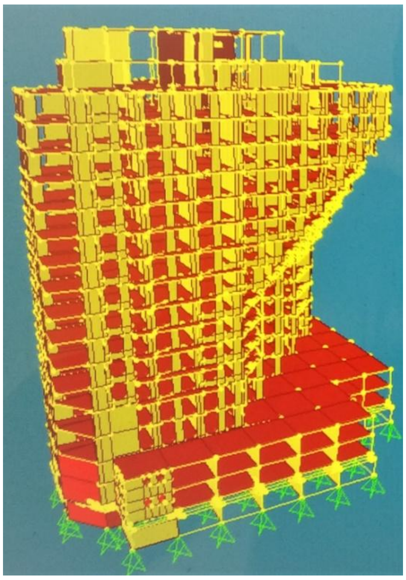
Table 1. Some results of analysis for the 18-story building of the multifunctional residential complex “Northern Ray” with and without seismic isolation

Design parameters	By the Armenian Seismic Code for:			
	base isolated building		fixed base building	
Period of vibrations (sec)	T_x=2.06	T_y=2.17	T_x=0.85	T_y=1.13
Inter-story drift (mm)	2.5	4.0	6.1	8.7
Horizontal shear force at the level of foundation (kN)	38786	41336	93151	81452
Displacement of the isolation system (mm)	133	141	-	-
	Average by the time histories for:			
	base isolated building		fixed base building	
Inter-story drift (mm)	1.4	3.4	3.8	9.9
Horizontal shear force at the level of foundation (kN)	47667	49240	86042	137872
Displacement of the isolation system (mm)	123	118	-	-

It follows from the obtained results that the first mode vibrations’ period of the base isolated building is longer than that for the fixed base building by a factor of 2.4 in transverse (X) direction and by a factor of 1.9 in longitudinal (Y) direction. Direct comparison of accelerations at the top level of the building shows that accelerations in the base isolated building are about 5 times smaller in average than in fixed base building. Results of calculations also show that inter-story drifts in base isolated building are in average 2.6 times smaller than those in fixed base building and horizontal shear forces are smaller by 2.3 times in average. It is also necessary to state that in none of the isolators the vertical force exceeds 1500 kN. Thanks to the proposed approach of location of rubber bearings by clusters in the seismic isolation system, a more or less uniform distribution of the vertical loads was achieved. The differences in vertical loads for various isolators do not exceed the factor of 1.5 and this fully corresponds to the requirements of the Armenian Seismic Code.

The above results clearly confirm the advantages of seismic isolation, which are also well illustrated by the Figure 8, where the limit deformed states for buildings with and without seismic isolation, are presented.

a.



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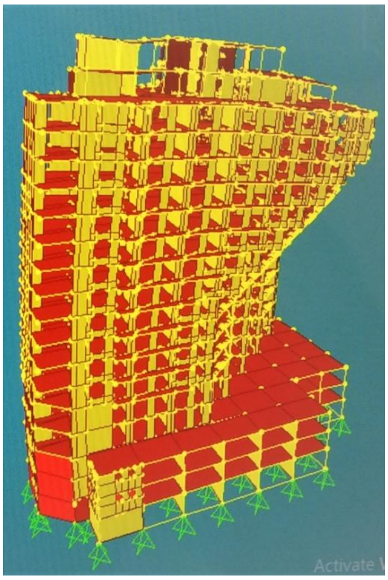

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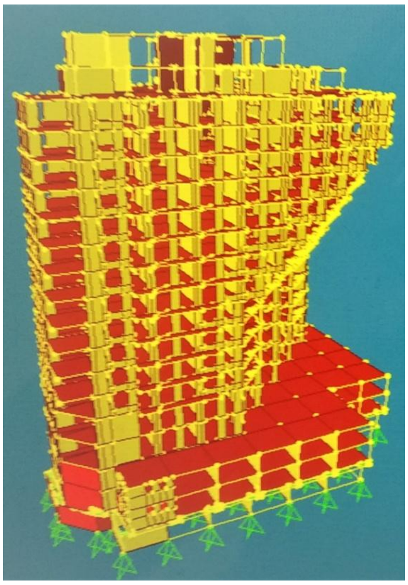

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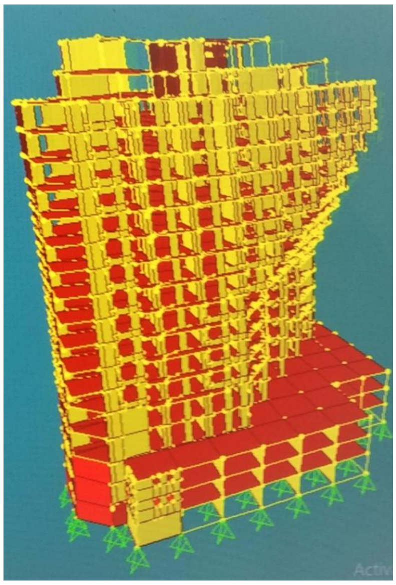

Figure 8. Limit deformed states of the 18-story buildings of residential complex “Northern Ray” with (a, c) and without (b, d) seismic isolation systems

Maximum horizontal displacement at the top of the seismic isolated building is equal in average to 71 mm and of the fixed base building – to 174 mm, which is bigger for about 2.5 times [5]. Calculations’ results have shown that the building without seismic isolation (having the same bearing structure as the seismic isolated building) is actually cannot withstand the ground input acceleration of 0.4g and will be destroyed. In other words to make the building without seismic isolation to carry the ground input acceleration of 0.4g, the cross sections of its bearing structures must be significantly increased. But this is the obvious disadvantage in comparison with the seismic isolated building.

2.3 Structural Concept of the 15-Story Base Isolated Apartment Building “Avan”

The other project financed by the governmental program for providing apartments for young families on analysis and design of 15-story base isolated building “Avan” was accomplished in 2010 [8]. Construction this building in Yerevan was completed in 2013 (Fig. 9). The considered building has a ground floor (envisaged for the offices) below the isolation plane designed using strong and rigid R/C structural elements. The cross section of columns here is equal to 600×600 mm and of beams below the seismic isolators – 600×400(h) mm and above them – 600×650(h) mm. The thickness of shear walls is equal to 200 mm. The cross section of the foundation strips is equal to 800x1500(h) mm. The accepted structural solution allowed obtaining a rigid system below the isolation plane, which provides a good basis for effective and reliable behavior of isolators during the seismic impacts. As it was mentioned above, the superstructure (which consisted of 14 residential floors) should have substantial rigidity for the same purpose. This was achieved by using R/C columns with cross section of 400×400 mm and 160 mm thick shear walls between them. The thickness of R/C slabs was set at 120 mm for all floors.

Figure 9. Design view of the 15-story base isolated apartment building of residential complex “Avan” and its current view

In this building again the approach on installation of the cluster of small rubber bearings instead of a single large bearing under the columns or shear walls was used. Corresponding examples of installed isolators are shown in Figure 10 from which one can see that different numbers of rubber bearings are installed in different clusters. All the medium damping rubber bearings (total 247 pieces) are also of the same size and characteristics as mentioned for the previous building.

Figure 10. Examples on installation of rubber bearings’ clusters in the 15-story base isolated apartment building “Avan”

2.4 Results of Analyses for the 15-Story Building “Avan” with and without Seismic Isolation System

The developed design model to carry out the earthquake response analysis of the considered building is shown in Figure 11. Calculations were carried out also considering the non-linear behavior of seismic isolation rubber bearings with the same input parameters as mentioned for the previous building. Also the same group consisting of 9 accelerograms was used, including a synthesized accelerogram. For this building the author has decided to draw the attention of the readers on the magnitudes of response accelerations for the buildings with and without seismic isolation system under the impact of the input maximum ground acceleration of 0.4g. Figure 11 shows that for the building without seismic isolation system amplification of acceleration on the top of the building reaches 1.11g, which is about 2.8 times bigger that the input ground acceleration.

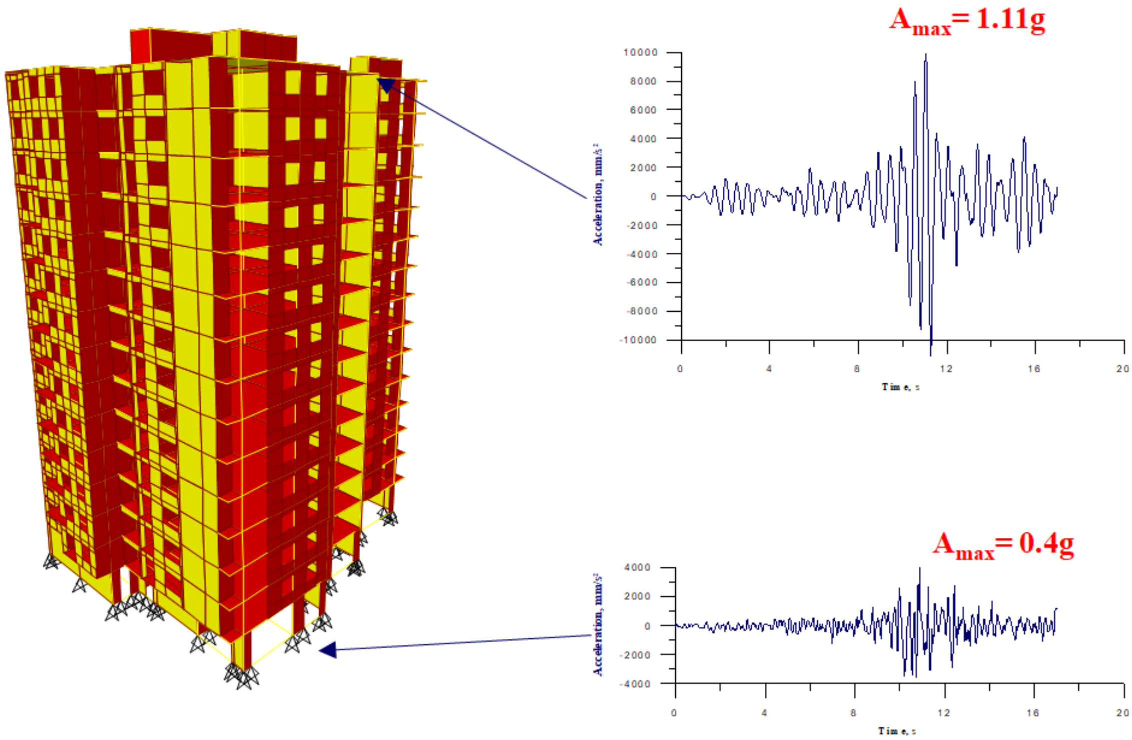

Figure 11. Response acceleration on the level of the top of 15-story building of residential complex "Avan" without seismic isolation system by the analysis in transverse direction using 1988 Spitak Earthquake acceleration time history

At the same time for the building with seismic isolation system the input maximum ground acceleration of 0.4g decreases in the superstructure. Figure 12 shows that due to implementation of seismic isolation response acceleration at the bottom of superstructure (on the level of the top of isolators) is equal to 0.14g and on the top of superstructure is equal to 0.16g. This means that seismic isolation brings to significant reduction (about 2.7 times in average) of the response acceleration in superstructure. That is why the author always mentions in his papers and articles that seismic isolation increases the quality of peoples' life as people feel earthquakes in seismic isolated buildings from 8 to 10 times less.

Maximum horizontal displacement at the top of this seismic isolated building is equal in average to 25 mm and of the fixed base building – to 67 mm, which is bigger for about 2.7 times. And again, calculations' results have shown that the building without seismic isolation (having the same bearing structure as the seismic isolated building) is actually cannot withstand the ground input acceleration of 0.4g and will be destroyed.

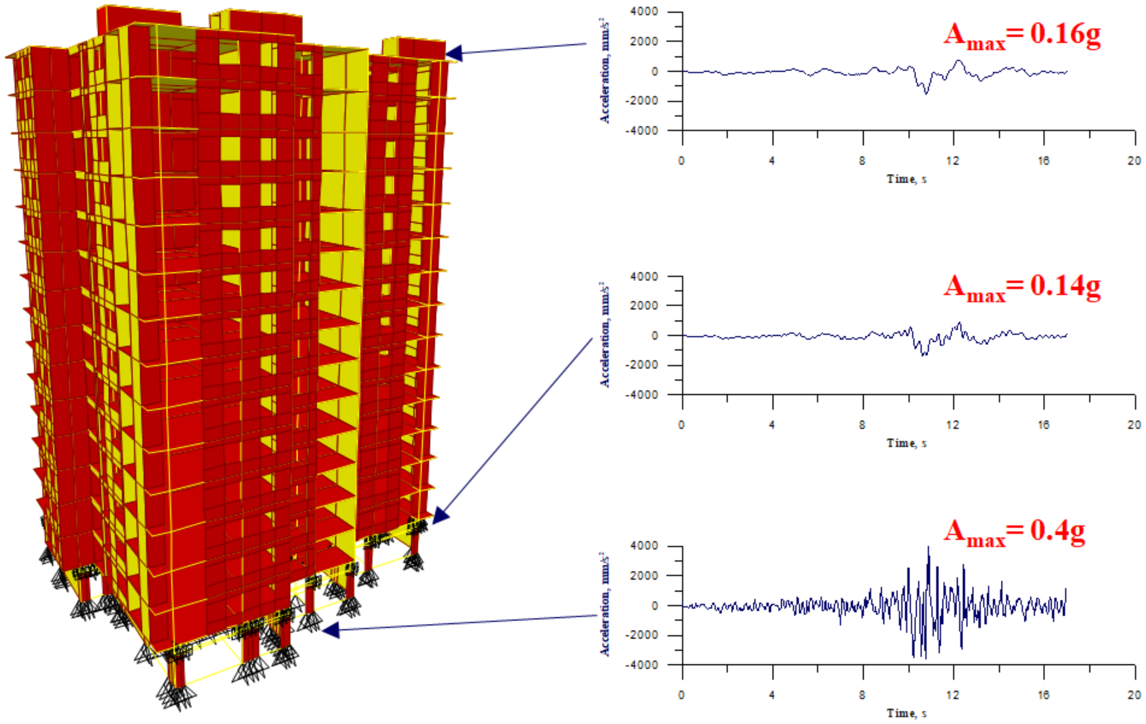

Figure 12. Response acceleration on the level of the top of isolators and of the top of 15-story building of residential complex "Avan" with seismic isolation system by the analysis in transverse direction using 1988 Spitak Earthquake acceleration time history

III. Conclusions

- Considering the soil conditions of Armenia where during the earthquakes mainly the high frequencies of soils' vibrations are prevailing, buildings with seismic isolation systems are the most relevant for highly resilient construction.
- Accelerations in superstructures of the base isolated 18-story "Northern Ray" buildings are about 5 times smaller in average than in fixed base buildings. Inter-story drifts in base isolated buildings are in average 2.6 times smaller than those in fixed base buildings and horizontal shear forces are smaller by 2.3 times in average.
- Maximum horizontal displacement at the top of the seismic isolated "Northern Ray" building is equal in average to 71 mm and of the fixed base building – to 174 mm, which is bigger for about 2.5 times.
- Due to implementation of seismic isolation the input maximum ground acceleration of 0.4g decreases in the superstructure of the 15-story "Avan" building. Response acceleration at the bottom of superstructure (on the level of the top of isolators) is equal to 0.14g and on the top of superstructure is equal to 0.16g. This means that seismic isolation brings to significant reduction (about 2.7 times in average) of the response acceleration in superstructure. However, in the building without seismic isolation system amplification of acceleration on the top of the building reaches 1.11g, which is about 2.8 times bigger that the input ground acceleration.
- Maximum horizontal displacement at the top of seismic isolated "Avan" building is equal in average to 25 mm and of the fixed base building – to 67 mm, which is bigger for about 2.7 times.
- Calculations' results have shown that the buildings without seismic isolation (having the same bearing structure as the seismic isolated buildings) is actually cannot withstand the ground input acceleration of 0.4g and will be destroyed.

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